WHOI-88-30

Gibraltar Experiment

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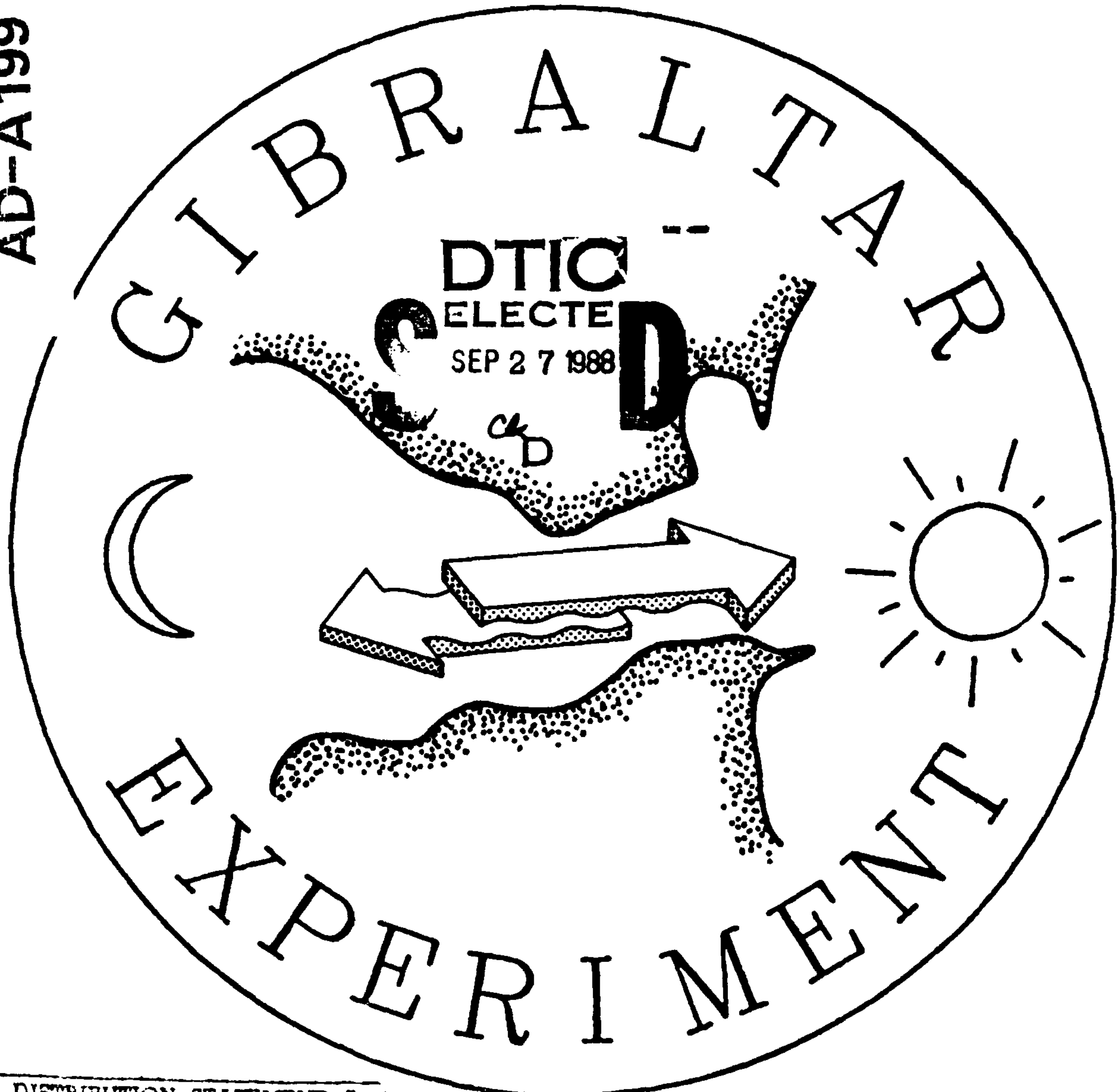

Summary of the Field Program and Initial
Results of the Gibraltar Experiment

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Technical Report

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Table of Contents

A-1

Summary of the Field Program and Initial Results of the Gibraltar Experiment

by
Thomas H. Kinder and Harry L. Bryden

Abstract

During the period October 1985 to October 1986 a large group of oceanographers collaborated in an intensive field effort called the Gibraltar Experiment. Scientists from Morocco, Spain, France, the United Kingdom, Canada and the United States joined together to obtain an extensive suite of measurements which greatly enlarged the oceanographic data base for the Strait of Gibraltar. Primary experiment goals included obtaining one realization of the annual flow cycle, understanding the dynamical balances of the strait flow, developing strategies for long-term monitoring of the Strait, and increasing knowledge of strait effects on the adjacent ocean. Preliminary results show progress toward each of these four goals.

1. Motivation

The Strait of Gibraltar has attracted interest for centuries (Deacon, 1971). Early inquiries concerned the process by which the inflowing surface water could be accommodated into a mass balance for the Mediterranean Sea. Modern interests have shifted focus to the unusual character of strait dynamics, such as the problems of high speed stratified rotating flow in the presence of irregular bottom and side boundaries, and to the mechanisms by which straits affect the adjacent oceanic environment (Bryden and Stommel, 1984).

Early attempts at generalizing the physical oceanography of straits resulted either in accounts that were almost pure description (Zubov, 1956), or in a dynamical analysis which appears to over-emphasize friction (Defant, 1961). More recent thinking has emphasized the dynamical importance of nonlinearity in the momentum equations, both because of the implications of internal hydraulic control on the surrounding ocean and of the distinct nature of strait dynamics that is thus implied. An estimate based on data from the 1960's by Armi and Farmer (1985) showed that critical flow, that is internal (densimetric) Froude numbers equal to one, is likely for the Strait of Gibraltar. The Froude number is the ratio of the advection speed to the speed of a gravity wave, so that, for critical flow, disturbances cannot propagate upstream. This condition is called hydraulic control, in the sense that downstream changes (e.g. lowered pressure) do not influence the upstream conditions, and so the critical section (Froude number = 1) 'controls' the flow. Canizo (1984) considered time dependence, friction, and variable cross-sectional shape, and he also predicted hydraulic control within the Strait.

Prior to the experiment, the Strait was already well known as an exciting location for strong internal motions (Jacobson and Thompson, 1934; Lacombe and Richez, 1982) which could propagate for at least 100 km into the Mediterranean (Kinder, 1984). Near the sill, tidal current changes of 3 m/s were thought responsible for generating internal waves or bores with vertical displacements exceeding 100 m. Additionally, the Strait was known to influence profoundly the hydrography and flow in the adjacent Alboran Sea (Parrilla and Kinder, 1987) and Gulf of Cadiz (Howe, 1982; Armi and Zenk, 1984). In the Alboran Sea, the anticyclonic Alboran gyre evolves as the Atlantic water inflow exits the Strait of Gibraltar, while in the Gulf of Cadiz the Mediterranean outflow forms a subsurface plume which breaks up into discrete eddies. The spreading of the Mediterranean outflow as a salt tongue across the North Atlantic Ocean plays a central role in validating general circulation models (e.g., Worthington, 1976). The vigorous two-layer flow in the Strait, with fresher Atlantic water overlaying saltier Mediterranean water, transports about 1×10^6 m^3 s^{-1} in each direction, maintaining the salt and heat budgets of the Mediterranean.

Because of interest in both the intrinsic strait dynamics and the effects on the adjacent ocean, an international team of investigators (see Table 1), supported by the U.S. Office of Naval Research (ONR) in its initial discussion, selected the Strait of Gibraltar for an intensive field experiment. Improved understanding of some strait dynamics issues (e.g., hydraulic control) and improved instrumentation were the basis for anticipating a significant increase in understanding beyond the results of the large Strait of Gibraltar experiments in the 1960's (Lacombe and Richez, 1982). Improved hydrographic and velocity instruments and deployment techniques allowed much improved accuracy, greater resolution in both space and time, and much longer-term moorings. New techniques and instruments, such as microstructure probes, freon analysis procedures, and high frequency sonar permitted the collection of new types of data.

Pilot moorings were deployed for two weeks in the spring of 1984 to test the practicality of mooring design for the Strait. The results of this pilot study suggested that a good data return would be obtained from a longer deployment (Thompson *et al.*, 1985), and a decision to continue with a major experiment was made. A measurement period of one year was deemed reasonable for the observations, and the intensive field work was initiated in October 1985.

TABLE I. Gibraltar Experiment Participants

	Institution
	Internal Hydraulics
L. Armi	Scripps Institution of Oceanography, La Jolla, Calif.
D. Farmer	Institute of Ocean Sciences, Sidney, Canada
	Meteorology
R. Beardsley	Woods Hole Oceanographic Institution, Woods Hole, Mass.
R. Limeburner	Woods Hole Oceanographic Institution, Woods Hole, Mass.
C. Dorman	San Diego State University, San Diego, Calif.
J. Tapia Contreras	Instituto Nacional de Meteorologia, Madrid, Spain
A. Belhouji	Service Meteorologie, Casablanca, Morocco
R. Fett	Naval Environmental Prediction Research Facility, Monterey, Calif.
J. Haggerty	Naval Environmental Prediction Research Facility, Monterey, Calif.
	Seasonal Flow Variations
M. Bormans	Dalhousie University, Halifax, Canada
C. Garrett	Dalhousie University, Halifax, Canada
K. Thompson	Dalhousie University, Halifax, Canada
	Trace Elements
E. Boyle	Massachusetts Institute of Technology, Cambridge, Mass.
C. Measures	Massachusetts Institute of Technology, Cambridge, Mass.
A. Van Geen	Massachusetts Institute of Technology, Cambridge, Mass.
	Heat and Salt Transport
N. Bray	Scripps Institution of Oceanography, La Jolla, Calif.
	Current Meters
H. Bryden	Woods Hole Oceanographic Institution, Woods Hole, Mass.
C. Milleiro	Instituto Hidrografica de la Marina, Cadiz, Spain
D. Pillsbury	Oregon State University, Corvallis
	Freon
J. Bullister	Woods Hole Oceanographic Institution, Woods Hole, Mass.
	Turbulence and Dissipation
M. Gregg	University of Washington, Seattle
W. Nodland	University of Washington, Seattle
J. Wesson	University of Washington, Seattle
	Hydrographic Structure
T. Kinder	Naval Ocean Research and Development Activity, NSTL, Miss.
G. Parrilla	Instituto Español de Oceanografia, Madrid
D. Burns	Naval Ocean Research and Development Activity, NSTL, Miss.
	Hydrodynamic Modeling
D. Ouazar	Ecole Mohammadia d'Ingénieurs, Rabat, Morocco
N. Benmansour	Ecole Mohammadia d'Ingénieurs, Rabat, Morocco
M. Annaki	Ecole Mohammadia d'Ingénieurs, Rabat, Morocco
A. Benabdeljelil	Ecole Mohammadia d'Ingénieurs, Rabat, Morocco
H. Aboukir	Ecole Mohammadia d'Ingénieurs, Rabat, Morocco
L. Moutya	Ecole Mohammadia d'Ingénieurs, Rabat, Morocco
	Doppler Current Meters
N. Pettigrew	University of New Hampshire, Durham
J. Irish	University of New Hampshire, Durham
	Airborne Synthetic Aperture Radar
C. Riches	Universite de Paris, Paris
	Shore-Based Radar
G. Watson	Southampton University, Southampton, U.K.
J. Ives	Admiralty Research Establishment, Portland, U.K.
	Pressure and Sea Level
C. Winant	Scripps Institution of Oceanography, La Jolla, Calif.
A. Ruiz	Instituto Hidrografico de la Marina, Cadiz, Spain
J. Candela	Scripps Institution of Oceanography, La Jolla, Calif.

2. Objectives

The Gibraltar Experiment had four major objectives:

- Measure the inflow and outflow through the Strait for one full year in order to obtain a complete realization of the annual cycle;
- Directly assess the effects of rotation, friction, mixing, and nonlinear processes in dynamically controlling the flow;
- Define an efficient method for long-term measurement of the Strait flows so that interannual variability of the Atlantic–Mediterranean exchange can be monitored;
- Increase understanding of the influence of the Strait upon the adjacent ocean.

All elements of the experiment were directed toward one or more of these objectives, although individual investigators addressed many other, more specific objectives within this general framework (Bryden and Kinder, 1986, 1987). Examples of such objectives included determining the source of the trace metal enriched plume which flows into the Mediterreanean, investigating the participation of Western Mediterranean Deep Water in the outflow, delineating the evolution of the large internal waves from their generation near the sill until they enter the Alboran Sea, measuring the low frequency fluctuations in the flow and determining their relationship to atmospheric forcing, estimating the salt and heat transports in order to determine budgets for the Mediterranean, examining the relationship between the strait-scale flow and the dissipation, understanding the seasonal flow cycle, and determining the effect of the strait orography on the low level wind field.

3. Experimental Plan

Energetic phenomena in the Strait of Gibraltar span many spatial and temporal scales. The most important scales are those which appear to influence the flow dynamics most directly. Key length scales are those dictated by the strait dimensions, about 60 km long by 20 km wide by 500 m deep. Special attention must be paid to the idealization of the Strait as a two-layer system, with an upper layer of 50–250 m thickness, so that both layers are sampled adequately. Temporal scales extend from semidiurnal to annual. There are current variations (and related hydrographic changes) comparable to the mean flow at tidal periods (semidiurnal, diurnal, and spring-neap). In the adjacent waters, the Alboran Sea and the Gulf of Cadiz, scales between basin-wide (about 100 km; e.g. the Alboran Gyre) and sub-mesoscale (about 10 km; e.g. the initial outflow plume) are related to the flow through the Strait. Within the Strait, the nonlinear and highly energetic internal waves appear at small spatial scales (about 1 km) and short periods (about 15 minutes). Turbulence and shear, appearing at small vertical scales (down to centimeters), but associated with the larger scales, are directly related to mixing. The regional wind field, on meteorological scales of several hundreds of kilometers is modified locally by strait-scale orography.

To resolve the appropriate oceanographic and meteorological variables over these relevant temporal and spatial scales, the experiment was divided into two parts: the synoptic shipboard measurements and the moored time series measurements. The two parts are complementary and closely linked, so the division is somewhat arbitrary. Table 2 summarizes the chronology for the field work.

The synoptic measurements included standard oceanographic instruments such as CTDs (conductivity-temperature-depth profilers) and XBTs (expendable bathythermographs) as well as special-purpose instruments such as AMP (advanced microstructure profiler). Small area CTD surveys covering most of the grid shown in Figure 1a were done during November 1985, March–April, June, and September–October 1986 (Kinder *et al.*, 1986, 1987). Large area surveys extending into the Alboran Sea and the Gulf of Cadiz (Figure 1b) were done during March–April and September–November 1986 (Bray, 1986; Ruiz *et al.*, 1986).

During October 1985 and May 1986, AMP, which measures velocity shear, temperature, and conductivity on vertical scales down to centimeters, was deployed repeatedly in the Strait. The AMP cruises also used a high frequency (120 kHz) backscatter sonar (Figure 2) and an acoustic Doppler current profiler. During April, an intensive synoptic program within the Strait used CTD, XBT, XSV (expendable sound speed profiler), acoustic Doppler current profiler and high frequency sonar.

There were also several concurrent chemical sampling studies. During March–April and September 1986 surface trace metal (cadmium, cobalt, zinc, and copper) and nutrient (nitrogen and phosphorus) samples were obtained continuously from an underway sampling system. During April, subsurface metal and nutrient samples were obtained to complement the surface data. Freon samples were obtained from vertical casts in both the Alboran Sea and Gulf of Cadiz during September–October 1986. Finally, aluminum, selenium, and beryllium samples were obtained in both the Alboran Sea and Gulf of Cadiz during October 1986.

Two sets of synoptic meteorological data were obtained. During June, 1986 soundings, surface observations (wind velocity, pressure, temperature and humidity), aerosols, and visibility data were taken during a CTD cruise within the Strait.

TABLE 2. Measurement Periods

	Measurements Taken
October 1985	microstructure
November 1985	small-scale CTD survey
March–April 1986	large-scale CTD survey, surface trace metal and nutrients
April 1986	acoustic backscatter, Doppler profiler, CTD (control sections), subsurface trace metals and nutrients, shallow centerline strait moorings, mid-depth acoustic profiler mooring, shore-based radar
May 1986	microstructure
June 1986	small-scale CTD survey, surface meteorology and soundings, shore-based radar, aircraft-borne SAR
June–July 1986	meteorology during Levantes
September–October 1986	large-area CTD survey, surface trace metals and nutrients, freon samples, metal samples (Al, Se, Be)
October 1985–October 1986	current meter moorings, acoustic Doppler profiler moorings, pressure gauge moorings, sea level gauges
April–October 1986	sill thermistor chain moorings

Notes: The two mooring deployments listed for April 1986 were for about 1 month duration. The November 1985 and June 1986 small-scale CTD surveys were tied to the phase of the tide. The March–April and September–October 1986 large-scale surveys included the small-scale grid but were not correlated with tidal phase.

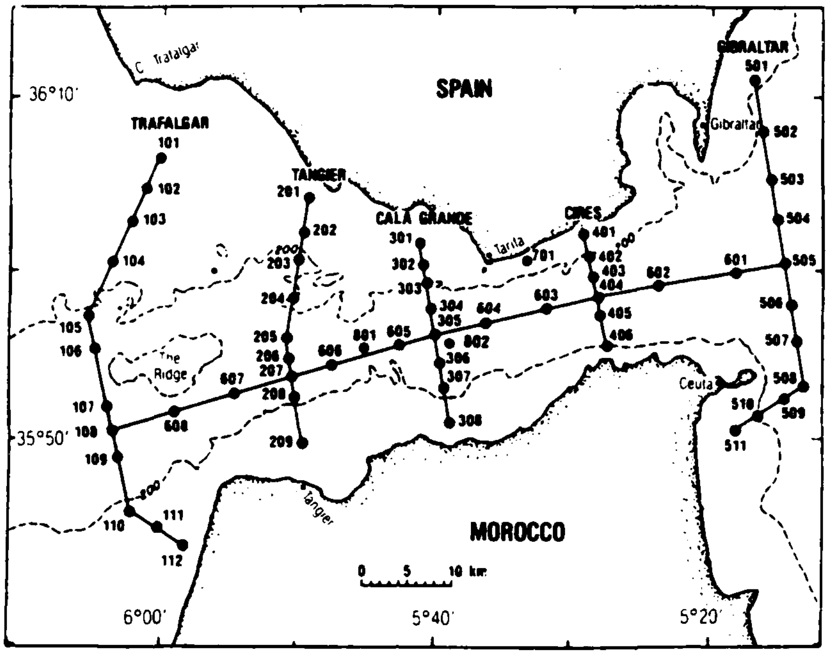


Figure 1a. CTD grid for small-scale survey. This pattern was used for surveys that were closely tied to the tidal phase in November 1985 and June 1986. The microstructure and April control section surveys (Table 2) used along-strait station patterns, whereas this grid emphasizes across-strait coverage.

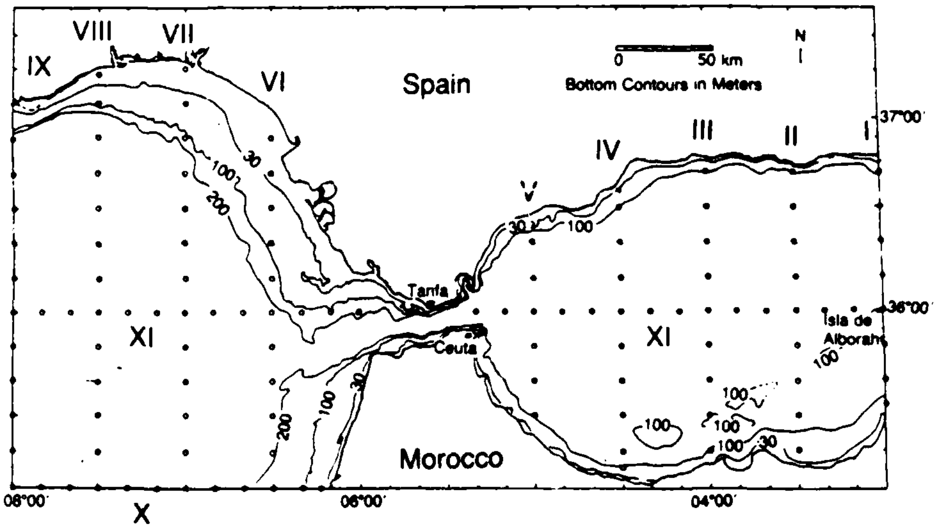


Figure 1b. CTD grid for the large-scale survey, done in March–April and September–October 1986. The small-scale grid (see Figure 1a) was included in each large-scale survey.

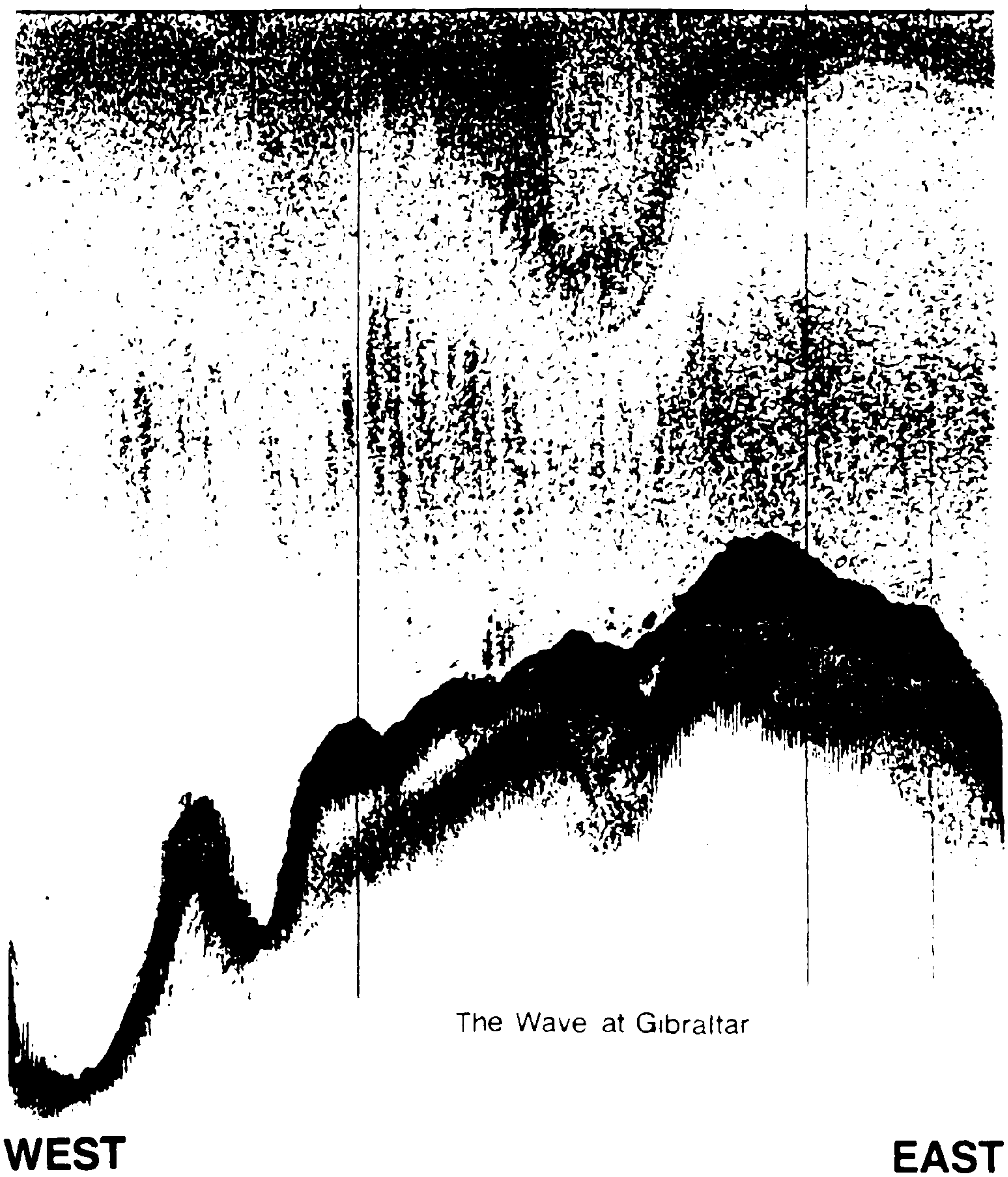


Figure 2. An image from a 120 kHz sonar system. The large depression is the lee wave west of the major (Camarinal) sill during the outflowing (westward) phase of the tidal current cycle. Estimates of the internal Froude number suggest that this cross section sometimes acts as a hydraulic control. The water depth near the apparent crest is about 300 m.

Surface observations and some soundings were made from the Tangier–Algeciras ferry in June–July during strong easterly wind events known as Levantes.

Additional synoptic measurements were obtained by aircraft, rather than ship. A B-17 research airplane carrying a Synthetic Aperture Radar (SAR) flew over the Strait on 22 and 24 June 1986 (Richez, 1987). This X band (9.37 GHz) radar system reveals the surface roughness patterns with a resolution of about 10 m.

The mooring array (Figure 3) was designed to measure the exchange through the Strait and the temporal variability at critical locations over tidal to seasonal time scales. During October 1985–April 1986, the long term current meter array of eight moorings covered the centerline of the Strait and the sill section. During April–October 1986, a reduced array of four moorings was deployed (Pillsbury *et al.*, 1987). Each of these moorings was intended to have one current meter in the upper Atlantic water at 75 m depth and one or more current meters in the deeper Mediterranean water. Because of bottom topography irregularities, the depth of the upper current meters varied from 30 m to 118 m. During the first period, four Doppler acoustic profilers were moored on the bottom, two each at the sill and at Tarifa Narrows. During the second period, one profiler was placed near the sill and one at Tarifa Narrows. During April 1986 a mid-depth Doppler profiler was placed in the center of Tarifa Narrows. Nearly all the current meters and Doppler profilers measured temperature, conductivity, and pressure.

During the April 1986 synoptic measurements, an additional array of four instrument moorings was placed along the strait centerline. Each mooring included current meters, thermistor chains, and pressure instruments (for mooring motion). Although designed to extend up to within 30 m of the sea surface, irregularities in bottom topography resulted in a minimum depth for these current measurements of 70 m.

The bottom pressure and sea level array, deployed from October 1985–October 1986 included a cross-strait array at the sill section, an along-strait array, and additional shallow pressure gauges near Tarifa, Algeciras, and Ceuta. These instruments supplemented the operational tide gauges network which is maintained in the Strait. The bottom gauges included temperature and conductivity sensors, and the tide gauges included temperature sensors. During the April–October 1986 period, thermistor chain moorings were maintained at each side of the sill section.

There were also two land-based "moorings". During October 1985–October 1986, meteorological stations were established at Tarifa, and also at Punta Cires on the Moroccan side in the narrowest part of the Strait. The stations recorded wind velocity, temperature, pressure, humidity, and insolation.

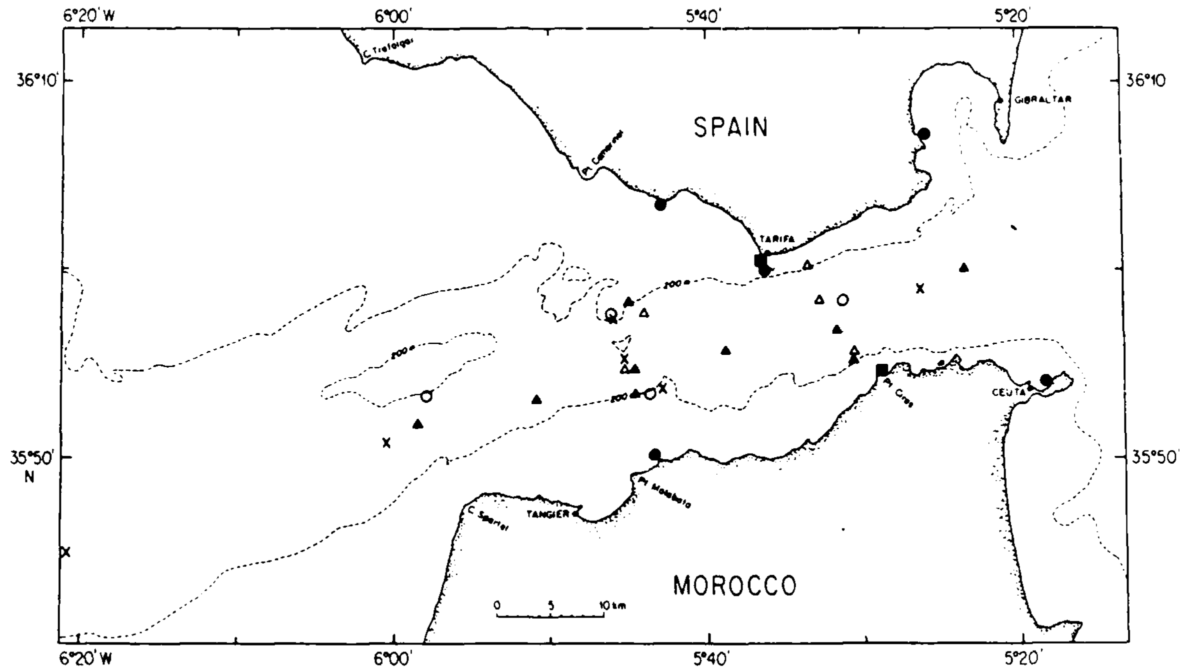


Figure 3. The mooring array. Not all locations were occupied for the duration of the experiment. The mooring array was designed to provide intensive coverage at one across-strait section (Camarinal Sill, northeast of Tangier), good along-strait coverage, and less intense coverage at a second across-strait section (in the narrowest part of the strait, east of Tarifa). The along-strait moorings generally follow the deep outflow path, which is south of the centerline west of the sill. Solid circles indicate sea level gauges, open circles are bottom pressure gauges, solid squares are meteorological stations, open triangles are Doppler acoustic profilers, closed triangles are current meter moorings, and crosses are thermistor chain moorings (the four crosses in the along-strait alignment included current meters).

A standard X band (9.4 GHz) search radar was used at Gibraltar during April and June 1986 to record surface roughness patterns (Watson, 1986; Ives, 1986). Although this radar had limited range to detect the surface roughness patterns associated with the large internal waves (about 15 km), it could collect long time series of such patterns.

Because of the rigorous strait environment, we anticipated some loss of instrumentation, both tethered and moored. The Strait has strong and variable currents, an irregular bottom, and dense shipping traffic. We were pleasantly surprised that no shipboard-tethered instruments were lost, in spite of the many casts made close to the bottom, in the vicinity of other vessels, and in conditions of rapidly changing currents. The loss of moored instrument data was somewhat larger than anticipated, however, as a result of multiple problems: wire failure, corrosion and wear of mechanical parts, release failure, and data logger failure. Many of these problems were unusual, and investigation as to the casues and the remedies continues. All three long-term (6 month) mooring groups encountered problems, although they used disparate mooring designs. The total data return from the mooring programs is substantial, however, with long time series of velocity, temperature, salinity, pressure, and sea level available at many locations. Many of the moorings that experienced failures also yielded high quality time series of short duration (e.g., one month). In this regard, the longest oceanographic time series within the Strait (aside from sea level) available prior to the main experiment was the two week long pilot experiment in 1984.

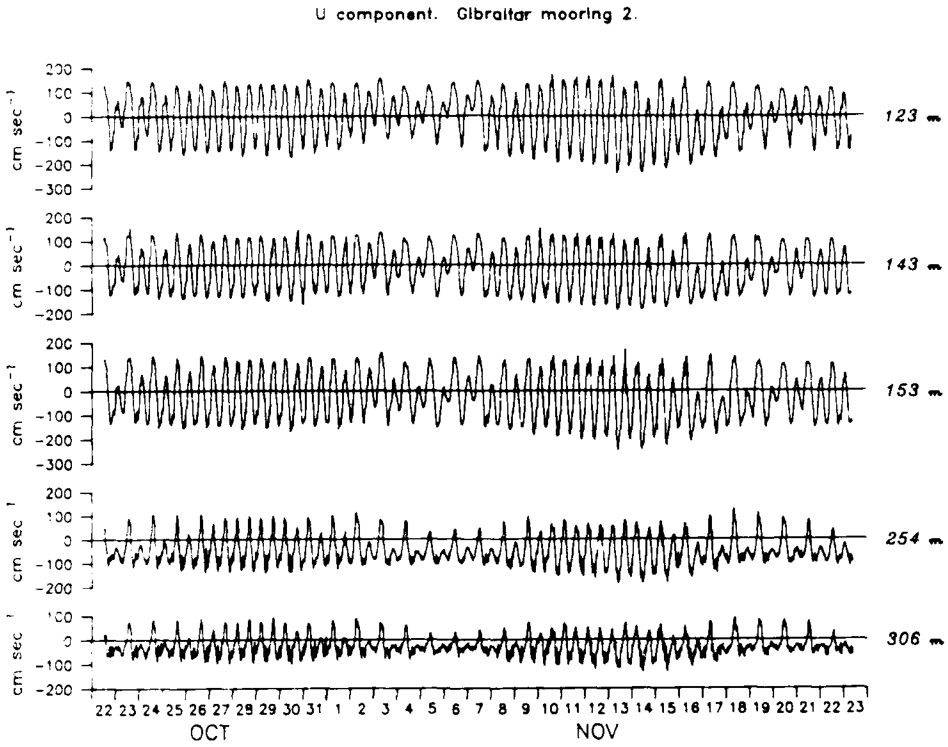
The field experiment has increased the conventional (e.g., hydrography and velocity) oceanographic data base for the Strait by at least an order of magnitude, added increased resolution to conventional measurements (e.g. modern CTD and mooring techniques), and provided unconventional measurements within the Strait (e.g. microstructure and trace metal concentrations). Overall, the data return is somewhat greater than we had anticipated, and it is certainly adequate to address the experimental goals.

4. Preliminary Results

Some preliminary results have already emerged from the field program. Many of these results were reported at the strait dynamics session of the Fall Meeting of the American Geophysical Union in December 1986 and at the marginal seas and straits session of the XIX General Assembly of the International Union of Geodesy and Geophysics in August 1987.

Considerable progress has been made on the mechanism of hydraulic control since Bryden and Stommel (1984) invoked this concept to explain major features of the Mediterranean. Armi and Farmer (1985) demonstrated that internal hydraulic control is likely to be effective within the Strait, and this led to a series of three papers that refined the concept of hydraulic control in straits, with particular emphasis on the Strait of Gibraltar. Armi (1986) elucidated the hydraulics of two-layer flows and the resulting coupling between the layers. This work was extended by Armi and Farmer (1986) to include barotropic flow through a contraction and by Farmer and Armi (1986) to encompass both sills and contractions. Bormans, Garrett and Thompson (1986) used the hydraulic theory to investigate the seasonal variations in the inflow that they infer from sea level data. They argue that the observed seasonal variation indicates a submaximal exchange through the Strait: that is, while the flow at the sill remains critical, the flow at the eastern exit of the Strait between Gibraltar and Ceuta is subcritical so that the amount of exchange varies seasonally with the level of Mediterranean water in the western Mediterreanean basin. Both groups have found confirmation in the early experimental results. Armi and Farmer ascribe hydraulically critical conditions to three sections at Tarifa Narrows, Camarinal Sill (the traditional and shallowest sill) and Spartel Sill (northwest of Cape Spartel) with supercritical flow at the eastern and western exits of the Strait at all times during their synoptic measurements in April 1986. Bormans and Garrett found subcritical flow on the Gibraltar–Ceuta section at the eastern exit of the Strait during the October 1985 synoptic measurements. Ouazar, Benmansour, Aboukir and Moutya (1986), who applied a simplified model to strait dynamics to predict the interface configuration along the Strait, including regions of internal hydraulic jumps, found that their solution for the interface depth agrees with a November 1985 along-strait hydrographic section. Clearly, the long time series measurements are needed to resolve these controversies.

Time series of current and salinity at the sill during October–November 1985 (Figure 4) illustrate the character of the flow in the Strait. Semidiurnal tidal fluctuations in the east-west current have an amplitude of order 100 cm s^{-1}, and there is a clear fortnightly variation in the amplitude of the tidal currents. The salinity time series can be used to infer the variation in the interface between Mediterranean and Atlantic waters: when the inflow is strong, the salinity is relatively low at each instrument indicating that the interface is relatively deep; similarly when the outflow is strong the interface is shallow. An initial estimate of the time-averaged outflow transport has been made from the measurements at the sill. Because of the strong velocity-salinity correlation, it is necessary to determine an outflow salinity transport rather than a mass transport. The outflow salt transport is estimated to be 1.5×10^6 ‰ m^3 s^{-1}, above the basic Atlantic water salinity of 36.2‰. Thus, this transport may be considered to be either a 0.7 $\times 10^6$ m^3 s^{-1}outflow of pure ($S =$



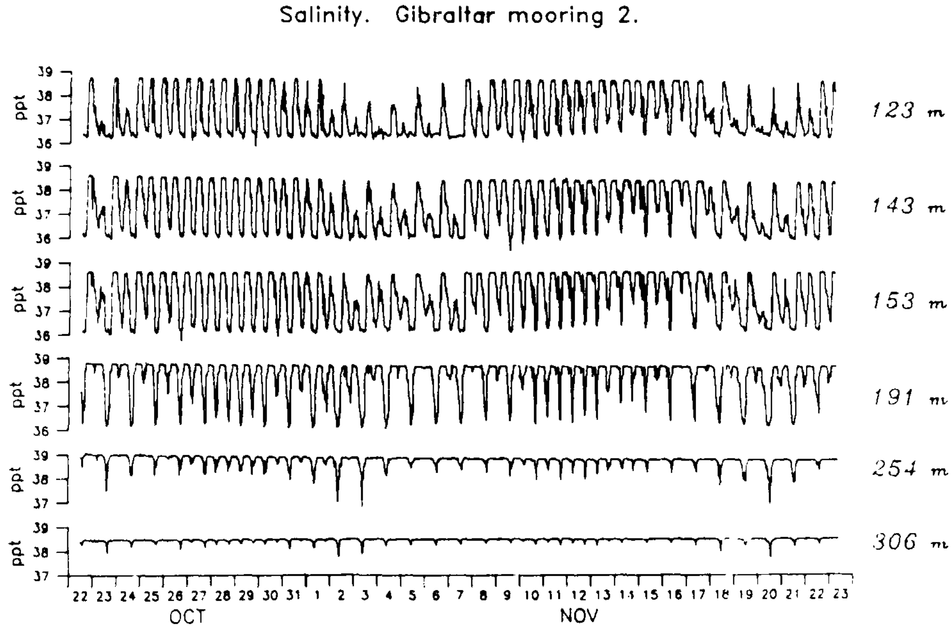


Figure 4. Eastward velocity and salinity time series for mooring 2 located at the sill during October and November 1985. Records shown are from current meters at depths of 123, 143, 153, 191, 254 and 306 m. The velocity record was not returned at 191 m depth.

38.4‰) Mediterranean water or a 1.1 $\times 10^6$ m^3 s^{-1} outflow of mixed ($S = 37.5$‰) Mediterranean-Atlantic water.

The low-frequency (periods longer than one day) fluctuations in inflow-outflow have amplitudes of order 40 cm s^{-1} and periods of order 15 to 20 days (Figure 5). These fluctuations are coherent vertically in both the Atlantic and Mediterranean layers and horizontally both across the sill section and along the entire axis of the Strait. Thus, these fluctuations probably correspond to large transport changes, though the fluctuations in interface depth have not yet been taken into account. As for seasonal variability, there does not appear to be an obvious annual signal in the long time series of velocity measurements at the sill (Figure 5).

The pressure and sea level measurements also indicate substantial tidal and subtidal fluctuations. For the semidiurnal tide at the sill, high tide occurs approximately 90° in phase before maximum eastward tidal flow; and the interface between Atlantic and Mediterranean layers achieves its minimum depth approximately 50° in phase before high tide, that is when the tidal currents are relatively close to maximum outflow. The semidiurnal tide is rapidly damped east of the sill and there appears to be a slight southeastward propagation evident in the phase of the tide. For the low-frequency fluctuations, the pressure difference across the Strait is strongly correlated with the along-strait velocity indicating a geostrophic balance for the subinertial frequency bands (Figure 6). An initial investigation of the atmospheric forcing of the low-frequency fluctuations in the exchange through the Strait suggests that the current fluctuations are correlated both with wind stress and with atmosperhic pressure over the Mediterranean basin. How to sort out these two interrelated driving mechanisms for the flow through the Strait is the focus of ongoing analysis.

The microstructure measurements have shown very high dissipation rates associated with the strait regime. Both the overturning just west of Camarinal Sill during Mediterranean water outflow and the internal wave propagating eastward from the Camarinal Sill following Mediterranean water outflow showed regions with high rates of dissipation that are 2–4 orders of magnitude greater than typical open ocean values (Figure 7).

Observations from the standard shore-based radar showed over 50 propagating internal wave packets, and also other features in the surface roughness patterns that may equate to predicted oblique waves (Farmer and Armi, 1986). The airborne SAR also showed a rich pattern of roughness features over the entire Strait,

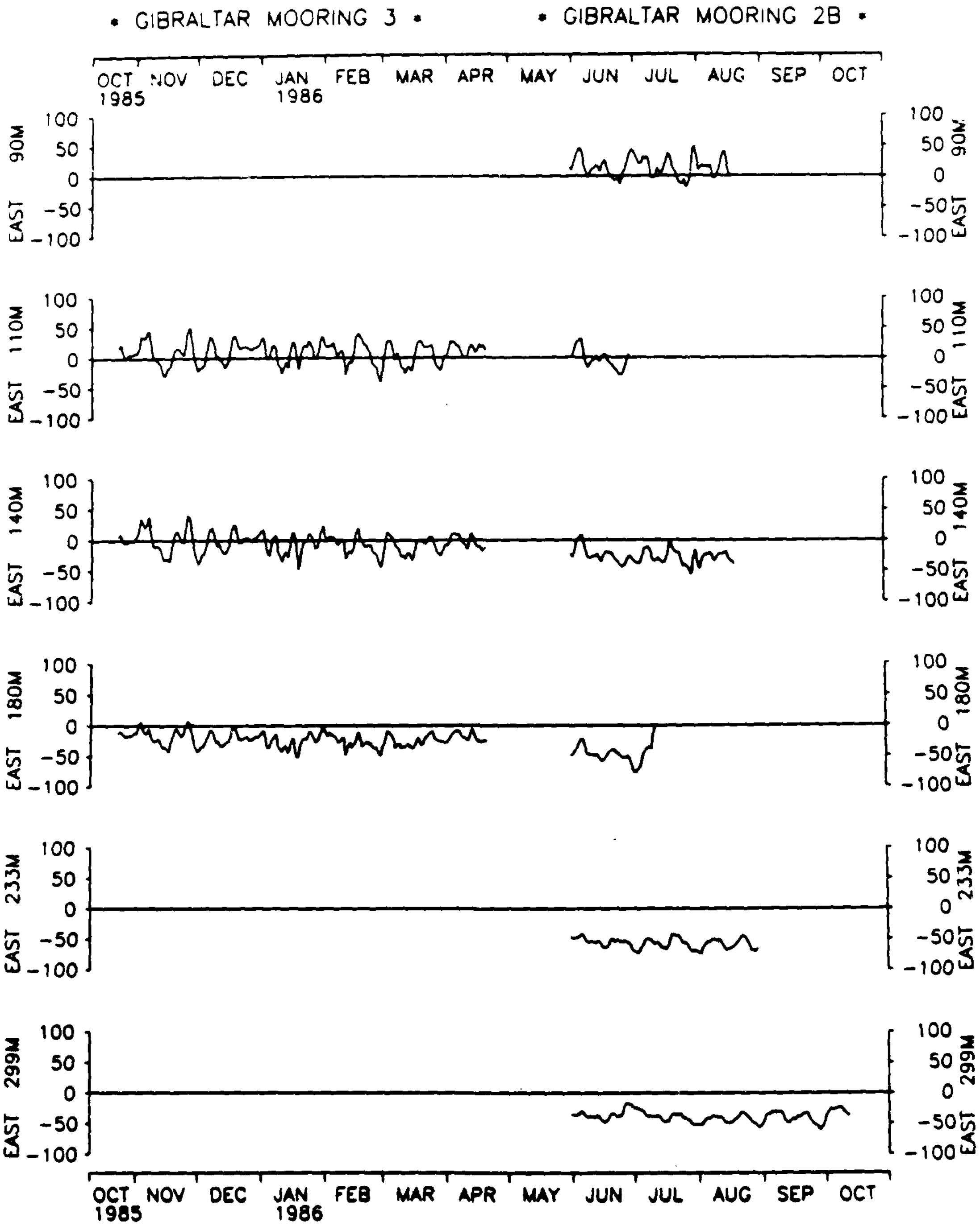


Figure 5. Year-long current measurements at the Gibraltar Sill. The eastward velocity time series shown are a composite of mooring 3 and mooring 2B records at depths of 90, 110, 140, 180, 233 and 299 m.

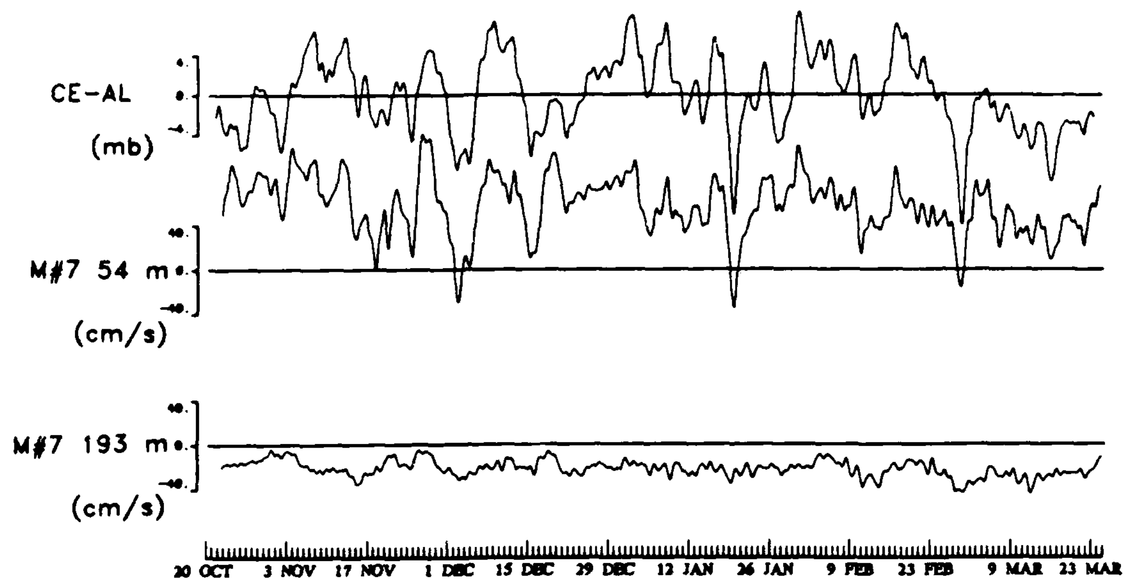


Figure 6. Low-passed current and sea level differences. The upper curve is the Ceuta (African side) minus the Algeciras (European side) sea level difference expressed as pressure (in millibars). The next two curves are along-strait currents from a mooring near the middle of the Strait between Ceuta and Algeciras (inflow to the Mediterranean is positive, in centimeters per second). The middle curve is from a current meter at 54 m depth that was nearly always in the Atlantic water, and the bottom curve is from a current meter at 193 m depth that was nearly always in the Mediterranean water. Note the strong correlation between sea level difference and Atlantic water velocity. Ticks on the 1985–86 time line are one day apart.

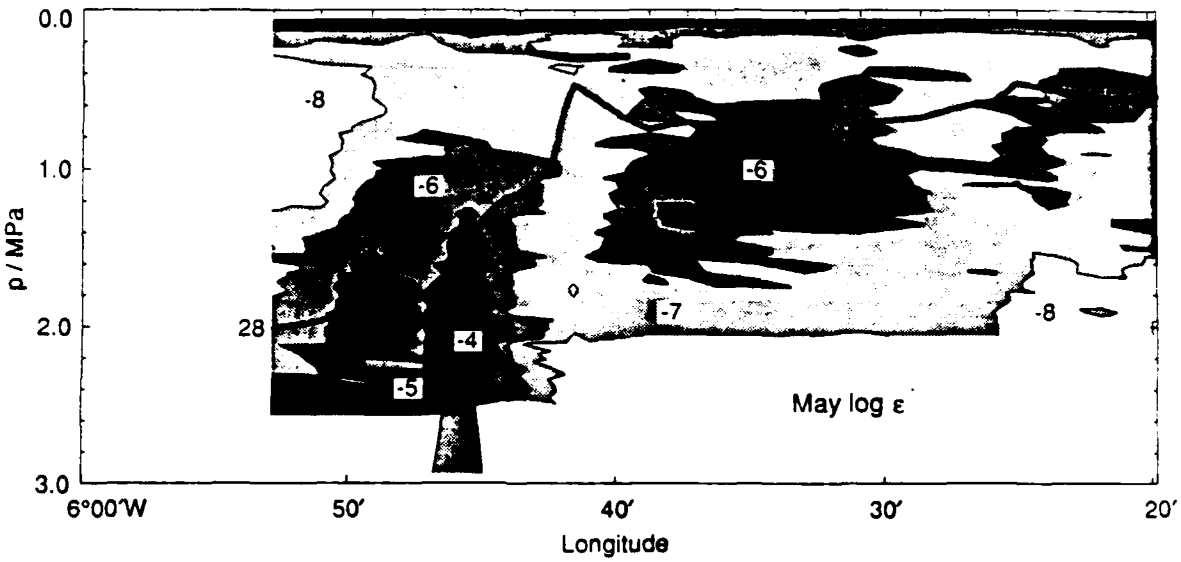


Figure 7. Dissipation for the average of nearly 1000 AMP profiles in May 1986. Peak dissipations occurred at Camarinal Sill in hydraulic jumps formed during strong outflow of Mediterranean water. Observations at the sill were two 12-hour sequences of AMP tow-yo's from west to east. The other dissipation maximum was at Tarifa Narrows (5°37′ W) produced by propagating bores that evolved into trains of solitary waves. Although many more profiles were taken in 6 days of profiling east of Camarinal, only three bores were seen. Therefore, the average in that region was determined by a few events. The heavy solid line shows the 28.0 σ_θ contour.

from the western to the eastern approaches, during the two days of flights which coincided with strong spring tides.

Early analysis of the meteorological data suggests that for at least some Levantes (a frequently occurring easterly wind), the strong winds in the Strait are not caused simply by acceleration through the constriction of the Strait. Instead, a thermal low over western Spain and Morocco accelerates the wind through the Strait as it flows down the pressure gradient. Wind speeds were higher west of Tarifa than at the narrowest part of the Strait. The effect of this Levante wind pattern on the Strait flow has not yet been determined.

The question posed by Stommel, Bryden and Mangelsdorf (1973) as to whether Western Mediterranean Deep Water (WMDW) participates directly in the Mediterranean outflow has been answered by the CTD surveys (Kinder and Parrilla, 1987). WMDW was detected in almost all near-bottom casts taken within a few kilometers west of the sill during both spring and neap tides (Figure 8).

Hydrographic time series data near the sill confirm a suggestion made by H. Lacombe (personal communication). The time lag between the ascent of the density interface at the sill and the time of high water is a strong linear function of the tidal coefficient (i.e., amplitude of the barotropic tide). During spring tide, the interface rises above 100 m depth 4–5 hours before high water at Tarifa (Figure 9), while during neap tides there is almost no lag. These spring-neap modulations of the temporal evolution of the interface height must affect the exchange of properties through the Strait.

Chemical sampling has demonstrated that the trace metal plume found in the Atlantic water inflow to the Mediterranean in 1982 (Boyle, Chapnick, Bai and Spivak, 1985) is persistent, and that one possible origin is the Spanish Atlantic shelf. If the shelf is the source, then this result confirms the belief of some local oceanographers that an important contribution to the inflow is made from these waters. Initial interpretations based on alunimum samples indicate that the Mediterranean water sampled in the Gulf of Cadiz had its origins in pure Levantine Intermediate Water, with no contribution from WMDW (Measures and Edmond, 1988). This intriguing result needs to be rationalized with the hydrographic results. The chemical sampling studies should add significantly to understanding about water mass origins and mixing.

5. The Future

The large data set that has been gathered is adequate to address the experimental goals, as the preliminary results demonstrate. The time series velocity

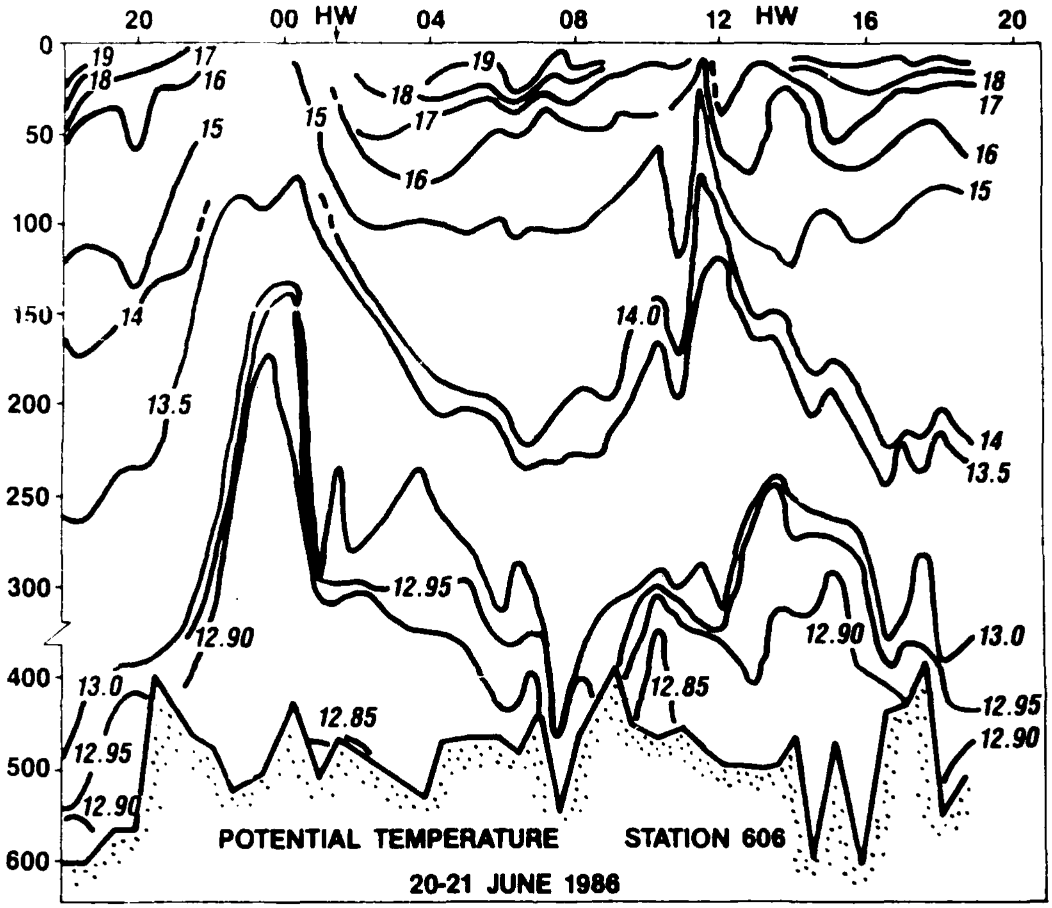


Figure 8. A time series of potential temperature taken about 3 km west of the major (Camarinal) sill during neap tides, June 20–21, 1986. With 50 separate CTD casts as its basis, this shows Western Mediterranean Deep Water (WMDW) defined by potential temperatures below 12.90°C west of the major sill and well below the sill crest (about 300 m depth).

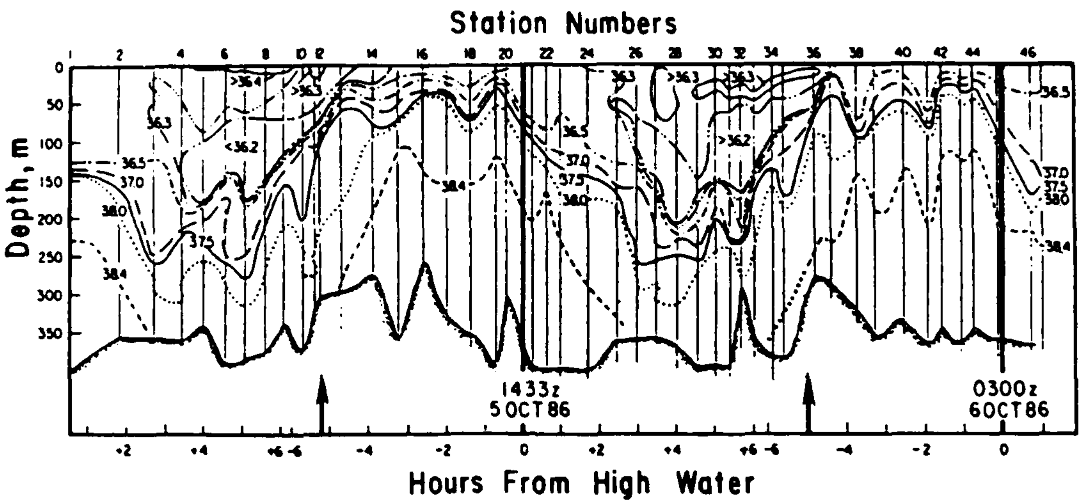


Figure 9. A time series of salinity on the south side of the Camarinal Sill, October 5-6, 1986, during spring tides. Note the lag of about 5 hours between the ascent of the interface (37.5 isohaline) to 100 m and high water at Tarifa. During neap tides there is little or no lag. From −6 to 0 hours in the tidal cycle, the barotropic tidal currents flow out of the Mediterranean.

data are sufficient to construct a year-long series of Mediterranean outflow. Ancillary data, such as hydrographic sections, sea level and pressure measurements, and velocity time series in the Atlantic layer (which are more sparse than in the Mediterranean layer) appear to be sufficient to estimate a similar series of the Atlantic inflow.

The data also permit direct dynamical assessments. Low-pass velocity and current measurements demonstrate geostrophic balance for the along-strait flow at subinertial time scales. Velocity, hydrographic, and acoustic measurements are being used to estimate Froude numbers and thus locations (and times) of hydraulic control sections. Shear and hydrographic measurements show variations in the turbulence and mixing, and thus the role of friction and mixing in the dynamics of strait flows can be quantified.

Strong correlations between across-strait sea level differences and along-strait Atlantic water velocities at subinertial frequencies give promise of a method for monitoring Atlantic inflow. The investigation as to whether the low frequency velocity and transport variations are related to atmospheric pressure or wind stress variations is being addressed, and it may offer an atmospheric predictor for strait transport. Bottom pressure measurements may be useful for monitoring the Mediterranean outflow.

Hydrographic and chemical sampling are showing the different origins and mixing histories of waters passing through the Strait. Initial calculations suggest that improved salt and heat budgets for the Mediterranean will emerge from the hydrographic surveys and the mooring data.

The most important task facing the Gibraltar investigators is to integrate their individual results into a synthesis that addresses the major experiment goals. Presently we are planning to present the results of the Gibraltar Experiment in a symposium at the University of Madrid in October 1988.

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INTERNAL HYDRAULIC STUDY: EXPERIMENTAL OVERVIEW

L. Armi and D. M. Farmer

Our experimental approach was designed to address specific aspects of the exchange process identified in a theoretical model of two-layer hydraulics. An analysis (Armi and Farmer, 1985) of the extensive historical data set of Lacombe and Richez (1982) showed that available observations were consistent with the concept of maximal exchange flow, hydraulically controlled at the narrowest section and also at the sill. The theoretical basis for this explanation was further developed by Armi and Farmer (1986) and Farmer and Armi (1986), including the influence of barotropic forcing. As a result of this work, it was apparent that certain key features of the exchange needed to be examined in order to verify the theoretical model, including the location of control points and the time dependent response. These considerations governed the design of our observational plan experiment and provide the essential framework for analysis of the results.

The main experimental cruise included an extensive set of profile measurements using both expendable devices and acoustic methods with the ship travelling rapidly, so as to acquire a picture of the dynamically important variables along the track. In addition, time series observations were obtained from the ship at certain key locations so as to determine the detailed structure of the tidal response. Complementing these ship-based measurements were data acquired simultaneously from moored recording instruments at four locations in the Strait. The combination of moored and shipboard data was considered essential to the proper description of the spatially and temporally variable flow.

Figure 1 includes a chart of the experimental area showing the principal ship tracks used together with mooring locations. These tracks consist of a run along the axis of the Strait, which we subsequently refer to as a 'run', and tracks across the Strait, which we call 'transects'.

The path of the longitudinal run represents a compromise between the need to obtain profiles along the east-west axis of the Strait, passing over the primary topographic features, and the navigational requirements of ship traffic separation. Positioning was achieved using radar ranging together with visual bearings where appropriate. For navigational simplicity the tracks were chosen, so far as possible, to be straight; ship positions were kept to within 0.3 nautical miles of the tracks, with deviations occasionally necessitated by traffic conditions.

Moored instruments

The moorings included a total of 13 Aanderaa current meters fitted with thermistors and conductivity sensors and 10 thermistor chains (see Figure 2). It was recognized that the strong currents in the Strait of Gibraltar required special care in mooring design and the use of substantial buoyancy and corresponding anchors, and of heavy mooring wire with extensive corrosion protection. As expected on the basis of our preliminary mooring modelling (c.f. Bell, 1979), large vertical excursions of the instruments were unavoidable. Thus, pressure measurements were essential and were included on all moorings. The Aanderaa design with its gimballed mounting is particularly suitable for moorings subject to significant inclinations in strong currents. The moorings were installed at the start of the April 1986 cruise and recovered at the end (see Figure 3).

Acoustic measurements

Two acoustic instruments were used from the ship: an acoustic Doppler current profiler and a high frequency echo-sounder. The echo-sounder is used as a flow visualisation device to provide graphic images of the internal structure of the flow. Sound is scattered by zooplankton, small fish and temperature microstructure. To the extent that these are distributed coherently with the density structure of the flow, the echo-sounder images can be used to visualise the dynamics. Some care is necessary in the interpretation, since the acoustic targets, especially the phototaxic zooplankton, have individual behavioural patterns. For example, a cloud of plankton may occur somewhat above or beneath the pycnocline; however, the pycnocline itself usually appears as a recognizable feature. The utility of acoustic imaging is greatly enhanced by simultaneous temperature or density profiles. The acoustic image then serves as a guide to the interpolation and interpretation of data obtained with expendable profilers while the ship is underway. Although there is substantial variability in the scatterer distributions, the broad features of the oceanographic structure are clearly delineated and help to confirm and enhance the interpretation of the profiled data.

Velocity profiles were obtained with a ship-mounted RDI acoustic Doppler current profiler. In order to avoid cross-talk between the Doppler profiler and echo-sounder, both instruments had a common trigger. The Doppler profiler has the facility for acquiring bottom track velocity, and where this has been obtained it has been incorporated in the profiles.

Two types of expendable profilers were used while the ship was underway: expendable bathythermographs (XBT) were used to provide temperature profiles and expendable sound velocimeters (XSV), to provide sound speed profiles which could be used in conjunction with the temperature profiles to generate salinity and density curves. When both XBT and XSV were used together, they were deployed simultaneously from opposite sides of the ship's fantail. Nevertheless, discrepancies in the designed drop speed, spatial variability in the salinity-temperature structure and other factors, produce unavoidable differences in the sampled volume, which leads to spikes in the computed salinity and density profile. These, however, do not detract from the value of simultaneous XBT/XSV profiles for identifying the pycnocline. More XBTs were available than XSVs, and we therefore used simultaneous drops more frequently at the western end of the Strait where the ambiguity in use of temperature profiles to locate the pycnocline is more pronounced.

Conductivity-temperature-depth (CTD) profiles were obtained at the ends of along-Strait runs and also during time series stations. For time series measurement the instrument was profiled continuously. With surface currents often reaching 2.5 m s^{-1} it was necessary to operate the CTD from the vessel's stern and to use 200 lb additional ballast on the instrument. A CTD mounted acoustic pinger and a towed hydrophone were used to control the depth of each profile to within a few meters of the bottom. Occasional surface and bottom samples were used to supplement the calibration data acquired before and after the cruise.

It was central to our experimental approach that data be analyzed during the cruise, so that modifications to the plan could be implemented as appropriate. Data from all ship-board measurements were available in real-time hard copy for analysis. A three-day break in the middle of the cruise was planned so as to allow evaluation of initial results and further planning of the concluding section.

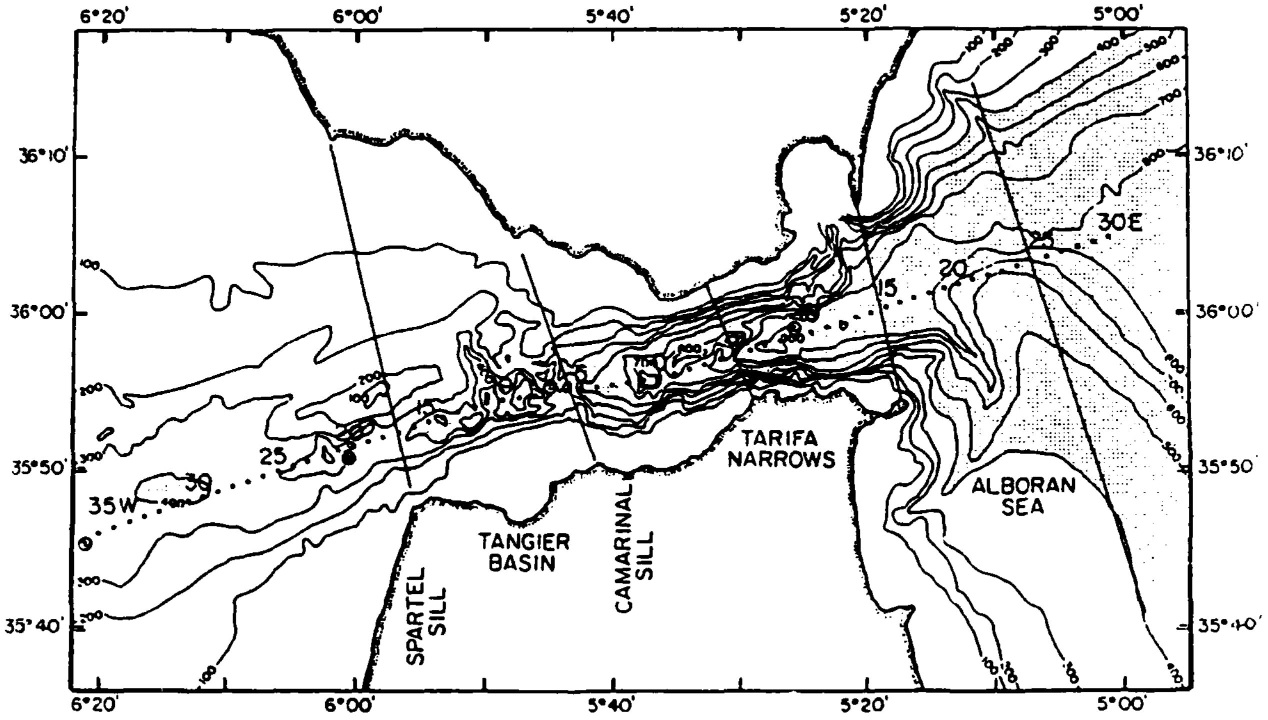


Figure 1: Chart of the experimental area with principal ship tracks and mooring locations.

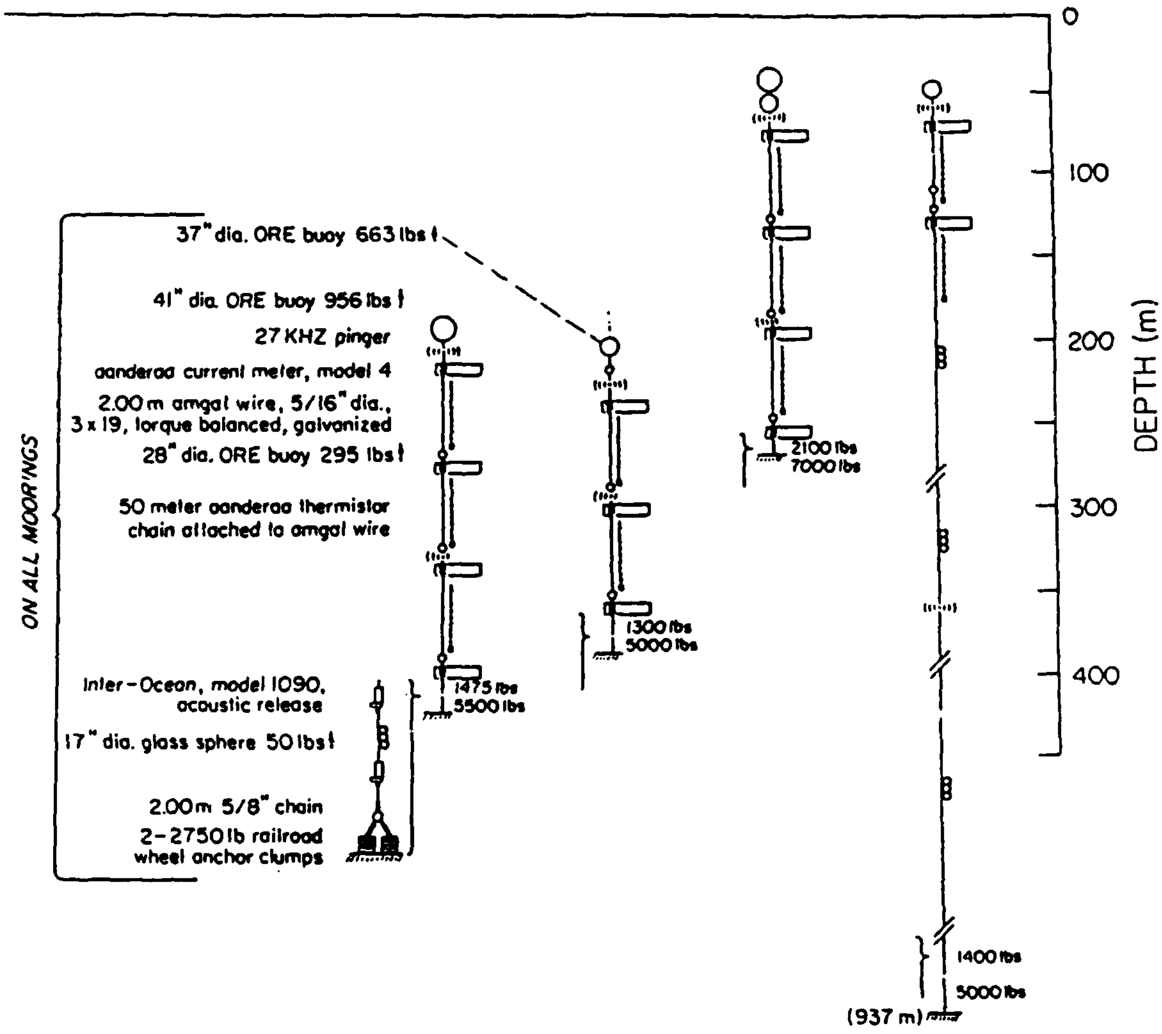


Figure 2: Schematic diagram of the moorings.

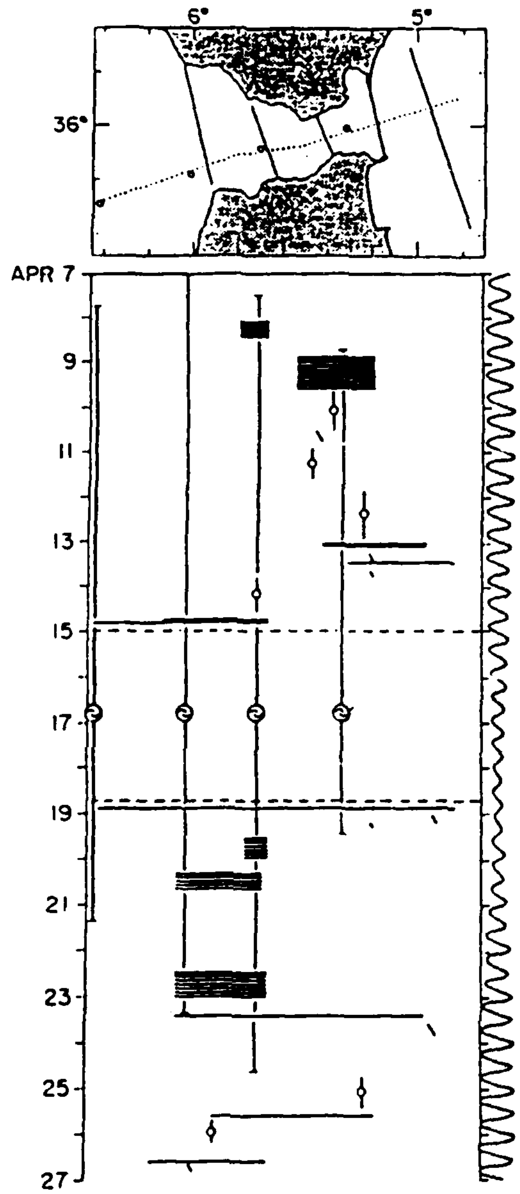


Figure 3: Detailed deployment time table.

SURFACE WIND AND MARINE BOUNDARY LAYER MEASUREMENTS IN THE GIBRALTAR EXPERIMENT

R. C. Beardsley and R. Limeburner

In October, 1985, we deployed, with ONR seed funding, two automated shore-based meteorological stations within the Strait of Gibraltar (see Figure 1), one at the Castilla Santa Catalina on the Isle of Tarifa, a low peninsula projecting southward into the Strait and directly exposed to the strong winds which can occur within the Strait, and one station on the Moroccan coast near an existing aid to navigation at Punta Cires. The shore stations measure and record the vector wind velocity, atmospheric pressure and temperature, insolation, and relative humidity. These two shore meteorological stations utilize WHOI (Woods Hole Oceanographic Institution) vector-averaging wind recorders (VAWRs). Output from the various sensors are averaged over 7.5 minutes and recorded internally on a Sea Data tape cassette data logger in the VAWR. A summary of the coastal meteorological data obtained in the Gibraltar experiment is given in Table 1.

In May, 1986, we recovered the two meteorological stations and found both instruments were flooded with water, a rather unusual state since neither instrument was deployed in the ocean. Basically, an electrical splice failed between the various sensors and the main instrument bulkhead connector cable. Water entered the instrument housing by wicking along the core of this multiconnector cable for a distance of 5 m. Both instruments were cleaned, rebuilt in Tarifa, Spain, tested and redeployed in May, 1986. Final recovery of the coastal meteorological instrumentation was in October, 1986. In addition, standard meteorological data collected by the Spanish at the Castilla Santa Catalina, Tarifa, has been collected (see Table 1), and this data set will be used to fill in gaps in our VAWR record from Tarifa.

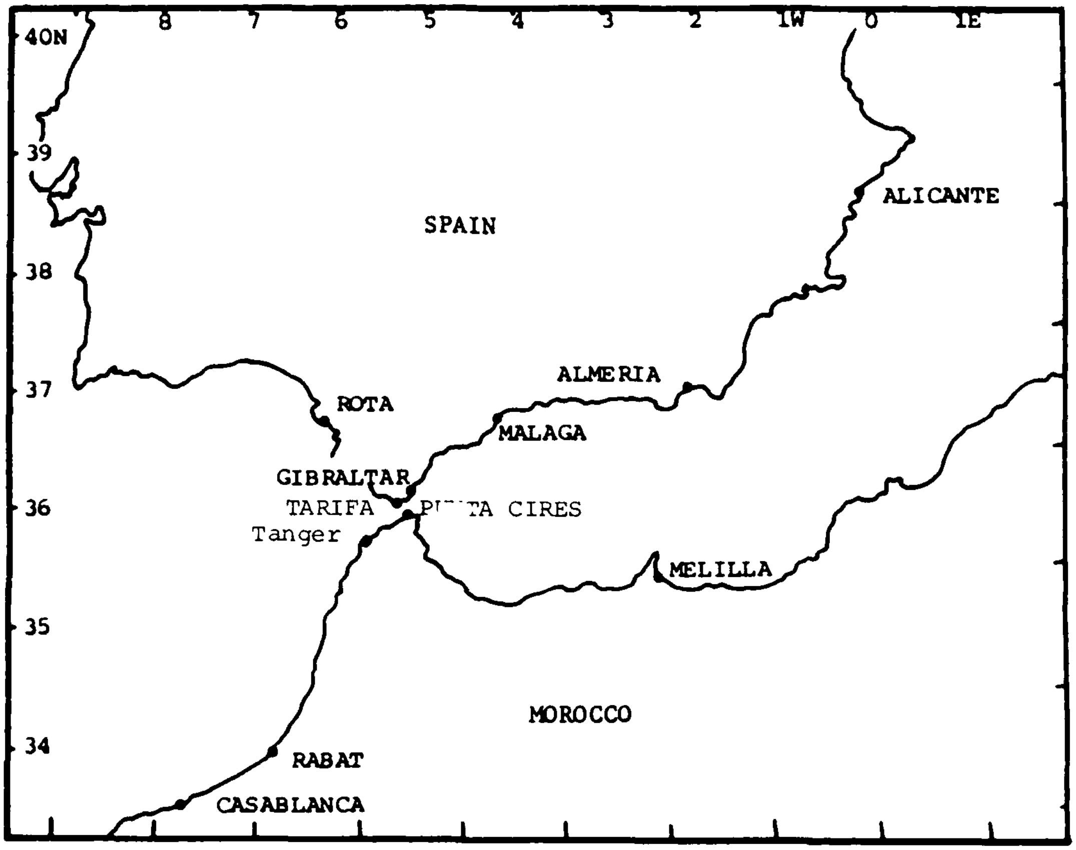


Figure 1. Locations of existing coastal meteorological stations and the W.H.O.I. stations at Tarifa, Spain and Punta Cires, Morocco.

Table 1: Coastal Meteorological Data Obtained in the Gibraltar Experiment

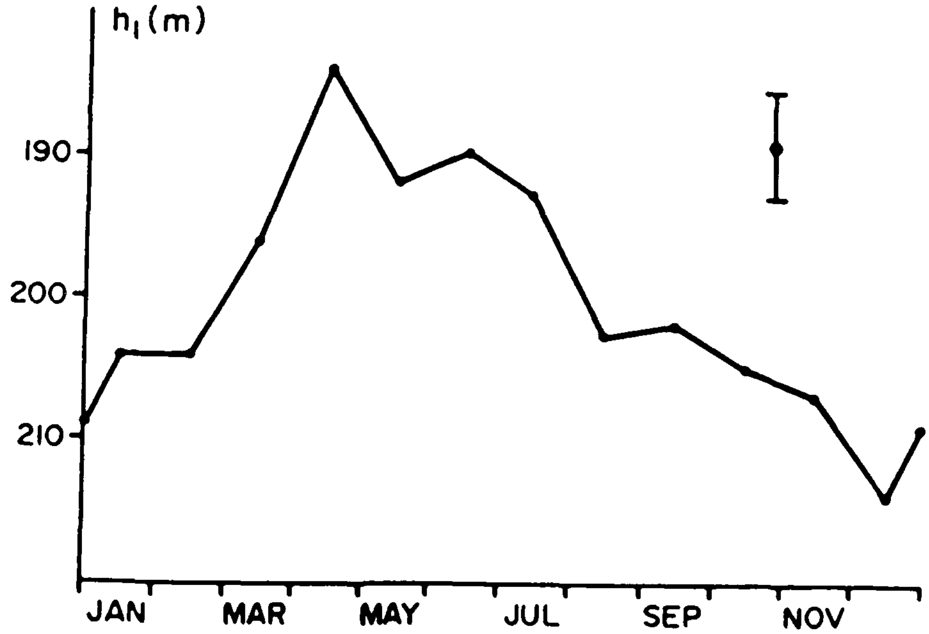
Name	Location (°N/°W)	Start/Stop (yymmdd)	Variable
<u>Morocco</u>			
Pt. Cires - VAWR 1	35°54.7'N 5°28.8'W	851008/851130 52 days	Windspeed, Direction, Air Temperature, Insolation, Barometric Pressure, Humidity
Pt. Cires - VAWR 2	35°54.7'N 5°28.8'W	860503/861007 156 days	Windspeed, Direction, Air Temperature, Insolation,
<u>Spain</u>			
Tarifa - VAWR 1	36°00.7'N 5°36.4'W	851008/851104 27 days	Windspeed, Direction, Air Temperature, Insolation, Barometric Pressure, Humidity
Tarifa - VAWR 2	36°00.7'N 5°36.4'W	860504/861016 166 days	Windspeed, Direction, Air Temperature, Insolation, Barometric Pressure, Humidity
Tarifa - Castilla	36°00.7'N 5°36.4'W	851001/860930 365 days	Windspeed, Direction, Wet and Dry Bulb Temperature, Barometric Pressure, Rain

SEASONAL VARIABILITY IN THE FLOW THROUGH THE STRAIT OF GIBRALTAR

M. Bormans, C. Garrett and K. Thompson

Historical sea level data from Gibraltar and Ceuta show seasonal changes in the surface inflow into the Mediterranean, with more than average surface inflow in the first half of the year, less than average in the second half. Using two-layer hydraulic theory we associate these changes in flow with changes in the depth of the interface between the inflowing Atlantic Water and the outflowing Mediterranean Water. In particular we predict that the monthly mean interface depth should change by 20 meters or so in the course of the year; we hope that data from the Gibraltar Experiment will confirm or disprove this.

Multiple regression analysis shows that part of this seasonal variability is related to changing wind stress (with dynamically plausible response coefficients). The residual variability in predicted thickness of the upper layer at Camarinal Sill is shown below.



This remarkable pattern is just what one would expect if the reservoir of outflowing water is replenished by deep convection and mixing in late winter and partially drains for the rest of the year. The result suggests that the Mediterranean is not in the "over-mixed" state that would lead to maximal exchange, but that the exchange is submaximal.

Full details of this analysis were presented in Oceanologica Acta, October 1986 (vol. 9, pp. 403-414).

The question of maximal or submaximal exchange is thus a key issue, which should be easy to resolve as the two possibilities correspond to supercritical or subcritical flow respectively at the eastern end of the Strait. Historical data is ambiguous on this point (possibly because of the effect of friction), but preliminary data from the Gibraltar Experiment suggest that the flow near the Gibraltar-Ceuta line was subcritical in October 1985, supercritical in May 1986 (M. Gregg, personal communication). Thus it seems that the flow through the Strait may be able to flip between these two different states, possibly in response to changes in wind stress, although we still suggest that submaximal exchange is the preferred mode. We hope that data from the Gibraltar Experiment will be examined with this important question in mind, and that steps will be taken to ensure that interannual variability is monitored in the future.

As well as conducting preliminary studies of the effect of friction on the hydraulic exchange, we have included the effects of rotation and non-rectangular cross-section. We will continue these investigations. We also plan to study further the causes and consequences of a bimodal surface flow at the eastern end of the Strait, and relate it if possible to the nature of the Alboran Gyre.

TRACE METAL MEASUREMENTS

E. Boyle and A. van Geen

The goal of this work is to determine the role of inflowing Atlantic surface, shelf, and North Atlantic Central waters in the trace metal budget of the Mediterranean Sea. A secondary goal is to reconstruct the mixing percentages of these various water types in the Alboran Sea, which will determine the importance of North Atlantic Central Water to the nutrient budget of the Mediterranean. This work follows upon the discovery of excess trace metals in the surface waters of the Mediterranean Sea and a metal-enriched plume in the Alboran Sea inflow.

We have participated in three of the Gibraltar Project cruises; two were on the Lynch expeditions of Kinder and Bray (March/April and September) and another was on our own shiptime on the Oceanus (April). The two Lynch cruises were used for synoptic transects of surface waters on either side of the Strait. On the order of 200 surface water samples were collected on each of these cruises. The Oceanus cruise was used for investigation of metal variability and sources in Spanish and Moroccan coastal waters. Seventy surface water samples and 70 subsurface samples from 14 profiles were collected on the continental shslf and Strait on this cruise.

We expect that there are four major water types (for trace metal contents) in this area:

(1) Surface open-Atlantic water,
(2) Subsurface North Atlantic Central Water (NACW),
(3) Shelf water (which is a mixture of the above types with additional contributions from river and shelf sediment sources, and
(4) Deep Mediterranean Water.

Of course, each of these types will have further subdivisions such as Levantine Intermediate Water and Mediterranean Deep Water. These four divisions are made because they correspond to what we expect to be the major unique chemical signatures. Given concentrations (C) for trace metal j in each of these major types (k), each sample (i) of inflow water is a linear combination of these compositions:

$$C_{ij} = \sum_{k} f_{ik} C_{jk} .$$

Given enough tracers with sufficiently independent signatures, it is possible to calculate the mixing fractions f_{ik} for each inflow sample using quadratic programming techniques in an overdetermined system. If the tracers have the appropriate characteristics, redundancy serves as a check on the robustness of the mixing model. Given enough faith in the mixing model, these chemical measurements can then be combined with the physical measurements to determine the contribution of each of the potential source types to the metal budget of the Mediterranean.

So far, the laboratory analysis is just beginning, and we only have data for cadmium, phosphorus, salinity, and preliminary data for cobalt. Nonetheless, the new data proves that there is an excess source of cadmium in Spanish and Moroccan shelf waters. The Cd-P-S relationships for the potential sources allow us to determine two possible scenarios for the Alboran Sea Cd plume:

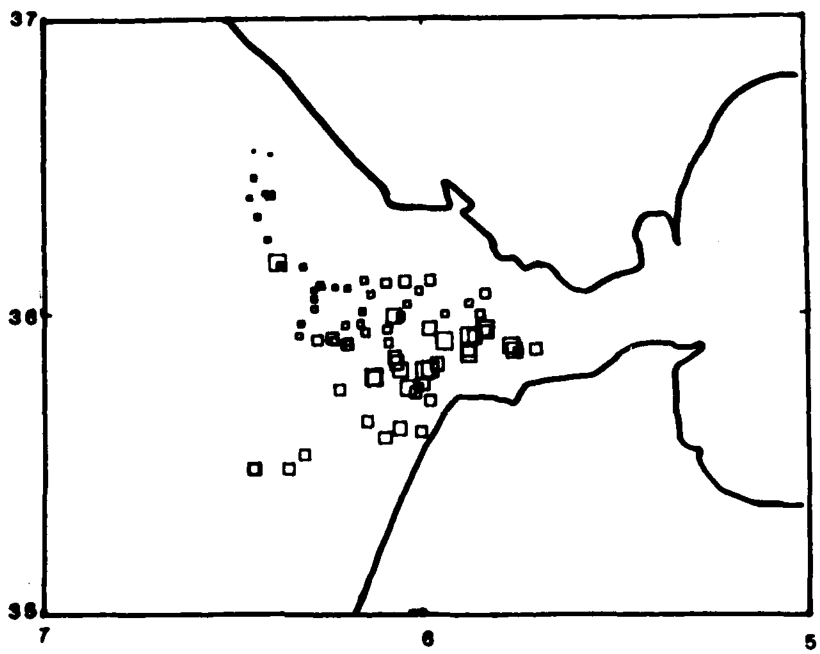
(1) Most of the Cd comes from upwelling NACW. In this case, the Alboran Sea plume is deficient in phosphorus, which must be removed by rapid biological activity.

(2) Most of the Cd comes from the shelf waters. In this case, phosphorus is conservative and there is no significant biological removal of phosphorus in the plume.

The difference between these scenarios has significant implications for the nutrient budget of the Mediterranean: scenario (1) would imply that NACW is the major source of phosphorus and nitrogen to the Mediterranean, while scenario (2) would assign NACW a role subservient to shelf sources.

We know from the old Alboran Sea plume data that zinc and copper should have signatures in the shelf water that will allow for a unique resolution to this scenario; we expect that ancillary Co, Mn and ^{228}Ra data will provide the smoking guns which seal the case beyond a reasonable doubt.

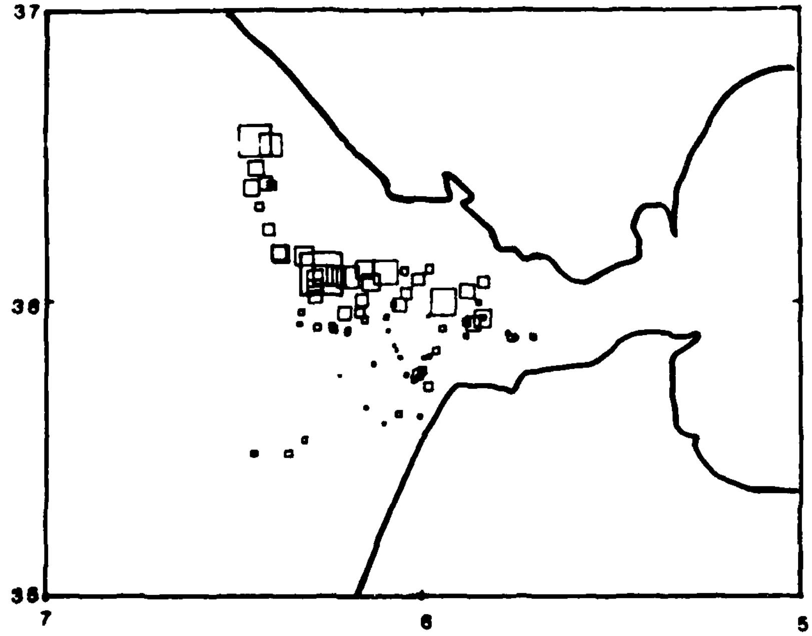
The following figures show the 1986 sample locations and surface cadmium distributions.



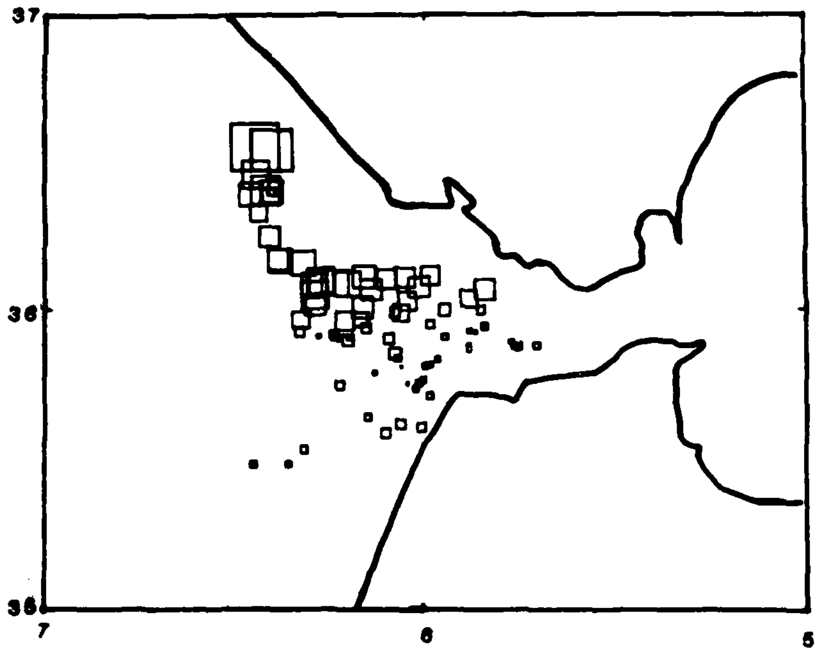
SALINITY - 35.90 ppt

symbol perimeter proportional to concentration

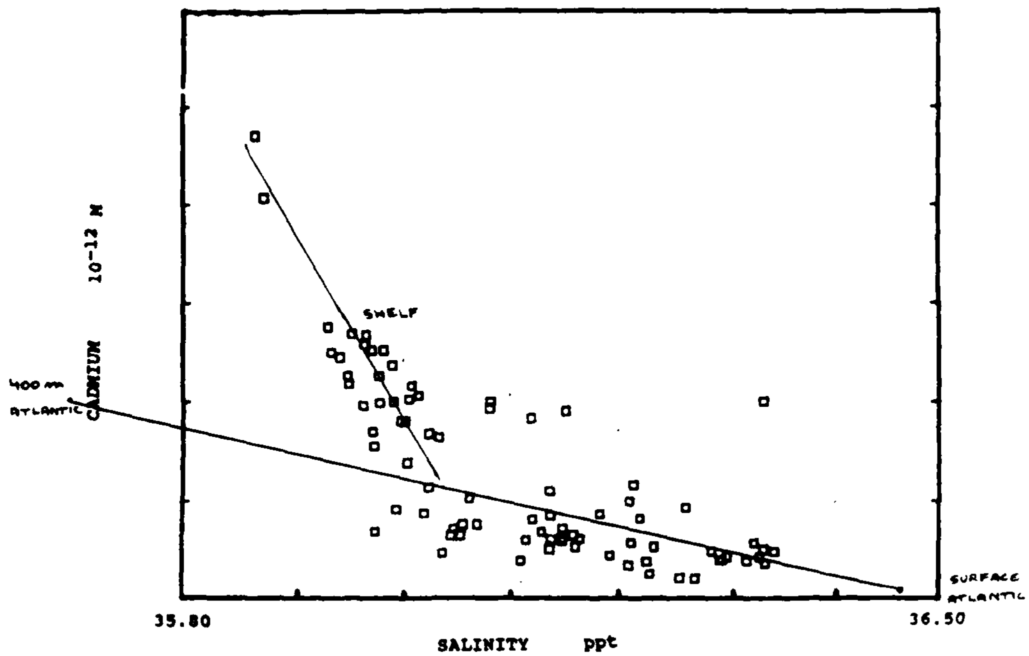
□ .3 ppt

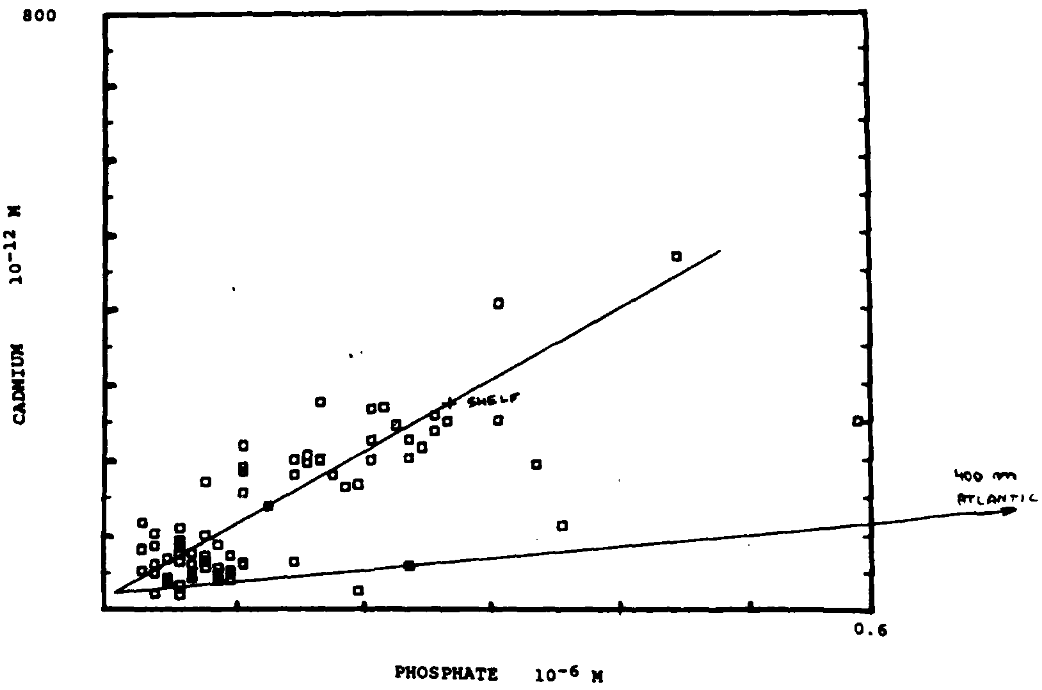


PHOSPHATE 10^{-6} M
symbol perimeter proportional to concentration
□ 0.2 μM



CADMIUM 10^{-12} M
symbol perimeter proportional to concentration
□ 200 pM


SHELF
400 m
ATLANTIC
CADMIUM 10-12 M
SURFACE
ATLANTIC
35.80
36.50
SALINITY ppt


800
CADMIUM 10-12 M
SHELF
400 m
ATLANTIC
0.6
PHOSPHATE 10-6 M

HEAT AND SALT TRANSPORT -- Status of Observations

N. Bray

Two cruises were conducted, 26 March to 19 April and 20 September to 11 October, 1986. CTD data from the first cruise, denoted GB1, have been published (Bray, 1986, Scripps Institution of Oceanography Reference Series #86-21, 212 p.) A data report for the second cruise, GB2, is in preparation. Both cruises covered the same large-scale grid, shown in Figure 1a below. Stations were also occupied within the Strait during both cruises, as shown in Figure 1b, and at time series stations shown in Figure 2a (GB1) and 2b (GB2). A total of 227 rosette stations and 6 time series stations (110 casts) were made during GB1. During the fall cruise, 179 rosette stations and 5 additional time series stations, totaling 198 casts, were occupied.

Preliminary estimates of geostrophic mass transport, heat, and salt have been made for Section VI, just west of the Strait. Vertical sections of potential temperature (Θ), salinity (S), density (σ_θ) and geostrophic velocity are shown in Figure 3. The heat flux associated with this section is 2 W/m^2 averaged over the area of the Mediterranean basin. The implied evaporation excess, or freshwater flux, is 69 cm/year, similarly averaged. While the latter agrees well with historical estimates, the heat flux is smaller than even the most optimistic error bars for atmospherically determined air-sea fluxes and is thus not easily compared. It is of the expected sign (Mediterranean losing heat to the atmosphere). Note that the reference level used for velocity calculations is the density surface between Mediterranean and Atlantic waters. It should also be noted that most of the exchange appears to occur north of the latitudinal axis of the Strait.

Time series stations were taken to examine tidal fluctuations in general in the Strait, and in particular to construct a composite picture of the cross-strait interface structure for use in estimating tidal transports of heat and salt. This composite is to be taken together with moored data (velocity, temperature, conductivity and pressure) to make these estimates. While the composites are still in preparation, preliminary plots of 24-hour series from GB2 north and south along the sill are shown in Figure 4. These salinity sections were drawn by hand, by H. Lacombe, from the corrected shipboard data. A correction of -14 ppm should be applied (i.e. values shown are high by 14 ppm). We show them here to illustrate the difference in structure from north to south: the interface is deeper and more diffuse in the south, and wave-like features are more pronounced. Diurnal variability is small in these plots, but this may not always be true (see Kinder, Parilla and Burns, this report). Tidal coefficients did not have much diurnal range during these stations, which were taken during the height of spring tides.

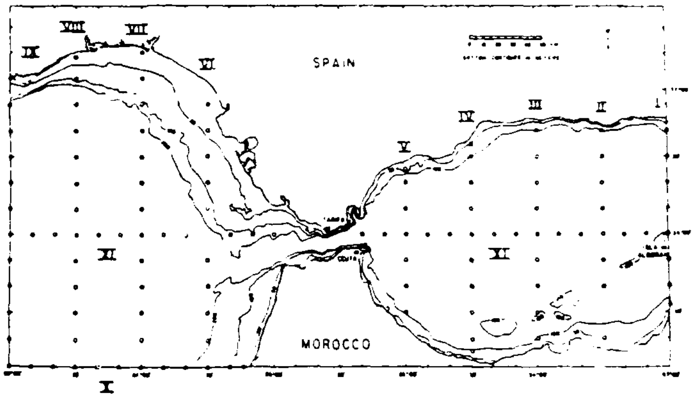


Figure 1a.

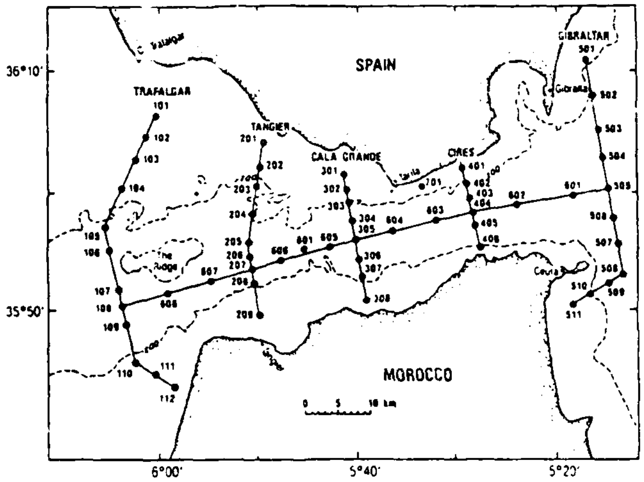
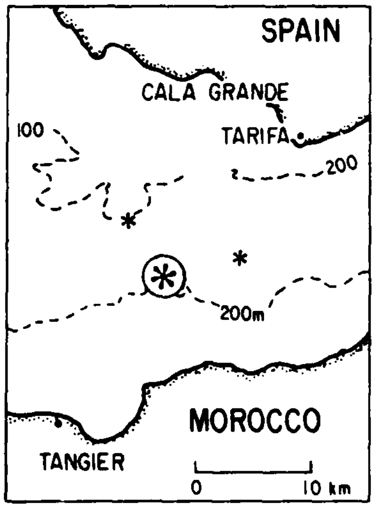


Figure 1b.



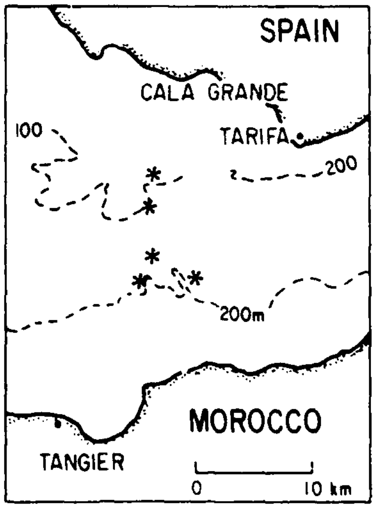
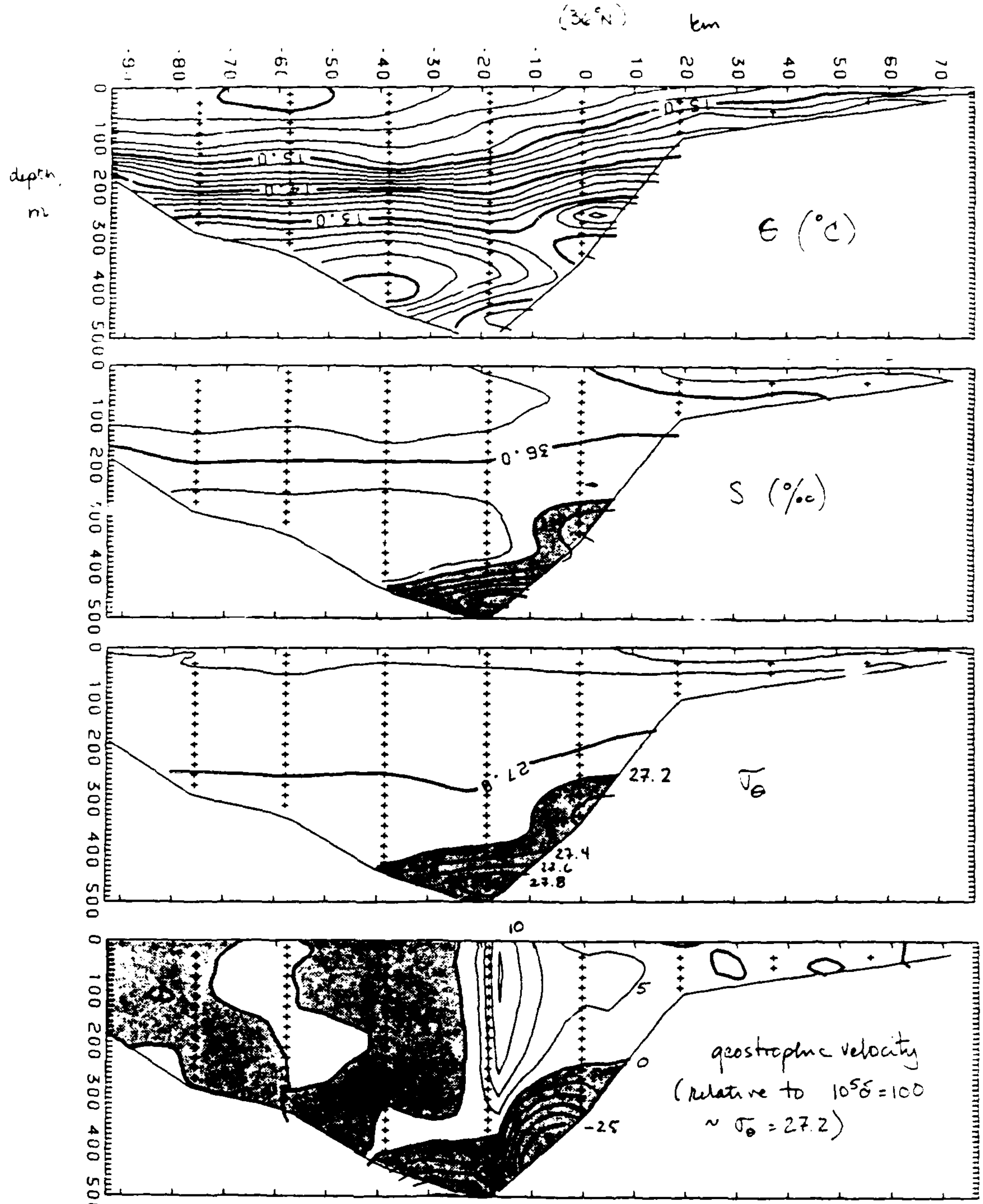


Figure 2a.

Figure 2b.



(36°N)
km
depth
m
Θ (°C)
15.0
14.0
13.0
S (‰)
36.0
σΘ
27.0
27.2
27.4
27.6
27.8
10
5
0
-25
geostrophic velocity
(relative to 10⁵δ = 100
~ σΘ = 27.2)

Figure 3.

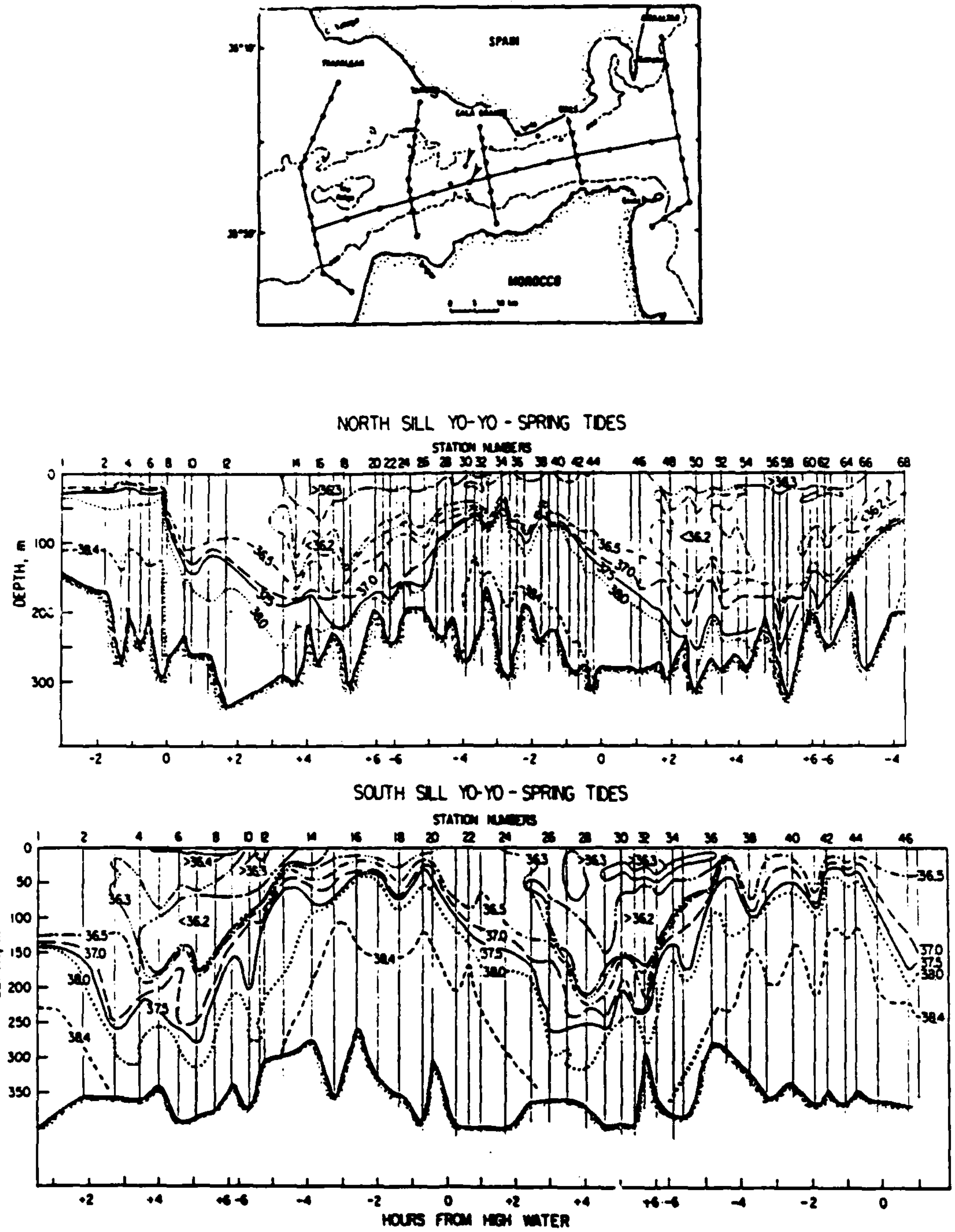

SPAIN
MOROCCO
NORTH SILL YO-YO - SPRING TIDES
STATION NUMBERS
DEPTH, m
SOUTH SILL YO-YO - SPRING TIDES
STATION NUMBERS
DEPTH, m
HOURS FROM HIGH WATER

Figure 4.

GIBRALTAR EXCHANGE MEASUREMENTS

H. Bryden, C. Milleiro and D. Pillsbury

A central component of the Gibraltar Experiment was the year-long moored array of current meters whose measurements are described here. Current meter moorings were maintained from October 1985 to October 1986 at a total of 9 locations in the Strait of Gibraltar (Figure 1). The purposes of these moored current meter measurements were to provide a year-long time series of the exchange across the sill section in order to examine its temporal variability over tidal to seasonal time scales; to determine the cross-strait structure of the velocity in both the inflowing Atlantic layer and the outflowing Mediterranean layer, and of the interface between the layers; to examine the along-strait propagation characteristics of the fluctuations in each layer; and to investigate the roles of friction, mixing, rotation and nonlinear processes in the dynamics of the flow through the Strait of Gibraltar.

In October 1985, eight current meter moorings (Figure 1, numbers C-1 through C-8) were deployed on a cruise aboard the Spanish naval vessel MALASPINA. Three moorings (C-1, C-2, C-3) across the sill section were densely instrumented in the vertical in order to measure the inflow of Atlantic water and the outflow of Mediterranean water across this transect of minimum cross-sectional area. Five additional moorings (C-4, C-5, C-6, C-7 and C-8) were deployed along the axis of the Strait in order to measure the characteristics of the flow at representative locations throughout the Strait. Mooring 4 is at a secondary sill, sometimes called Spartel sill, which is the last obstacle to the Mediterranean outflow before it cascades down into the Atlantic; mooring 6 is at the narrowest section of the Strait, sometimes called Tarifa narrows; mooring 5 is between the sill and the narrows; mooring 7 is at the eastern entrance of the Strait; and mooring 8 is in the deep Tangier basin between the sill section and the secondary Spartel sill. On each of these alongstrait moorings a current meter was deployed in the Atlantic layer at a nominal depth of 75 m and a current meter in the Mediterranean layer at a nominal depth of 230 m.

The Strait of Gibraltar is a harsh environment for current meter moorings with its high currents, high salinity and high oxygen Mediterranean water, and active fishing, shipping and naval operations. Typical water velocity is 100 cm s^{-1}, with tidal fluctuations appearing to be relatively depth-independent (Figure 2). The maximum measured current speed was 307 cm s^{-1}. To help design current meter moorings for the Strait of Gibraltar, a two-week pilot experiment was carried out in Spring 1984 near the site of mooring C-1 on the northern side of the sill section. Based on this experience, it was concluded that six-month moorings were feasible; that the mooring wire should be faired above 230 m depth; that buoyancy elements should be isolated large spheres rather than the more standard clusters of small glass balls to reduce drag; and that smaller, low-drag current meters should be used in the upper parts of the moorings whenever possible.

Despite the care in mooring design, only 3 of the 8 initial moorings (moorings C-1, C-2 and C-3) were recovered completely by the end of the initial six-month deployment. Parts of the other five moorings were recovered by Spanish and Moroccan fisherman and by the USNS LYNCH on the recovery cruise in April 1986. The principal problem appears to have occurred in the lower part of the mooring wire which was unfaired and unjacketed: high currents cause mooring wire vibration which flakes off the wire's galvanizing material and a galvanic action then corrodes the wire until it breaks under tension.

In May 1986, four moorings (Figure 1, moorings C-2B, C-3B, C-4B, and C-9B) were deployed for the second half of the year-long experiment on a cruise aboard Spanish naval vessel TOFINO. The problems from the first six-month deployment limited the size of the array for the second half to only four moorings. This second array was designed to be complemented by two Doppler acoustic profiling current meters deployed by Dr. Neal Pettigrew on the northern side of the sill section (extending the line of moorings C-3B and C-2B across the sill section) and on the northern side of Tarifa narrows across from mooring C-9B. For these current meter moorings, jacketed wire without fairing was used throughout each mooring. Of these moorings, only C-3B failed prematurely due to stress fracture of the tension bar on the S4 current meter at the top of the mooring. The final three moorings were recovered aboard USNS LYNCH in October 1986, although extreme vibration limited the duration of some of the instrument time series.

Nearly all of the current meters deployed in the Gibraltar Experiment were Aanderaa model RCM4 or RCM5 units which measured temperature, pressure and conductivity in addition to current speed and direction. Pressure is important for monitoring mooring motion; and temperature and conductivity are important for determining the salinity which identifies whether the current meter is in the Atlantic water, Mediterranean water, or the interfacial region between them.

Eastward velocity and salinity time series at the sill during October-November 1985 exhibit the character of the fluctuations in the inflow and outflow and in the interface between the Mediterranean and Atlantic waters (Figure 2). The temporal variability is principally due to the semidiurnal tides. At deeper levels, the flow is primarily directed westward out of the Mediterranean with some eastward flow during short portions of the tidal period. At shallower depths, there are increasingly stronger and longer periods of eastward flow into the Mediterranean. Mediterranean water, as indicated by salinities above 37.5 ppt, is always present at the deepest part of the sill. At shallower depths, salinity oscillates between 36 and 38.5 ppt indicating that the interface between Atlantic and Mediterranean waters is moving up and down past the instrument depth.

Despite all of the mooring problems and instrument malfunctions, a remarkable set of moored current meter measurements has been made in the Strait of Gibraltar. The year-long time series at the Gibraltar sill exhibit vertically coherent, low-frequency fluctuations in the Mediterranean outflow as well as strong tidal fluctuations. Further analysis of these current meter records should enable detailed investigation of the physical processes which dominate the dynamics of the two-layer exchange through the Strait of Gibraltar.

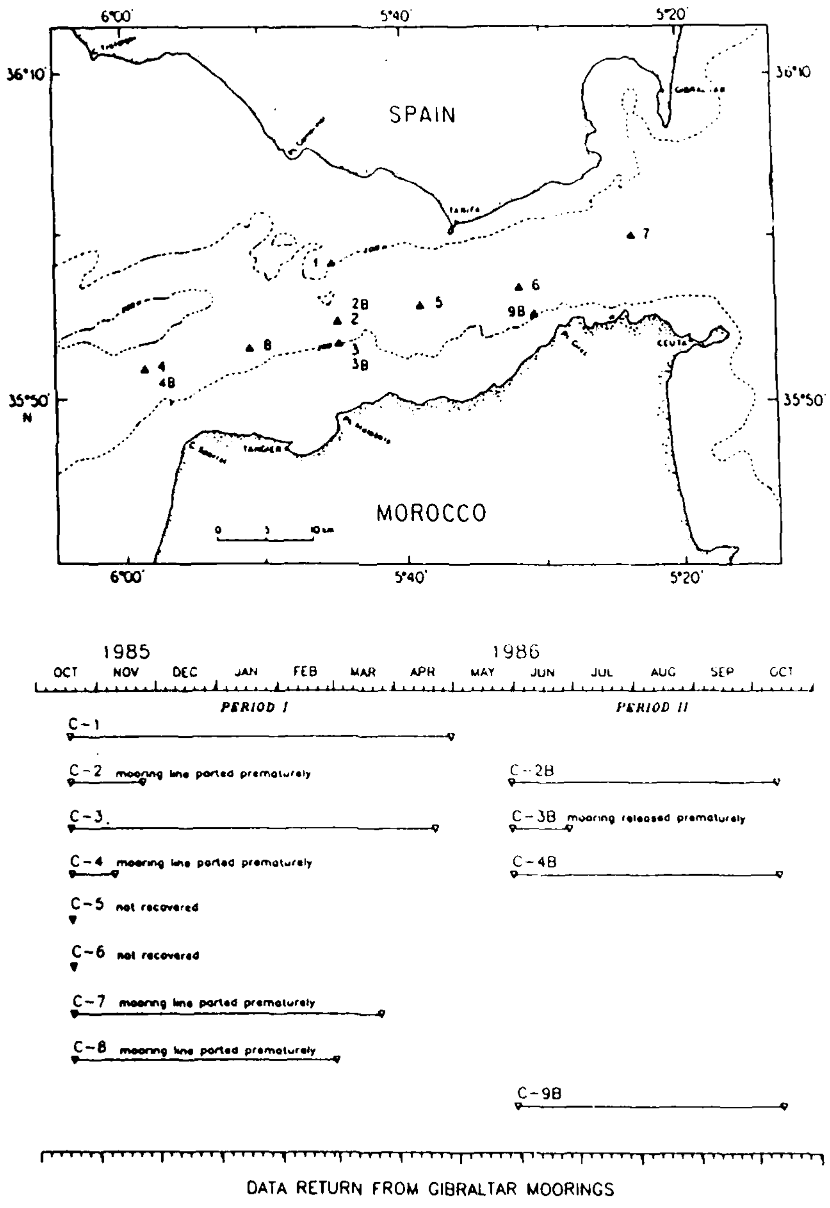


Figure 1. Site location of current meter moorings during the Gibraltar experiment, October 1985 to October 1986 and maximum duration of good data from each mooring.

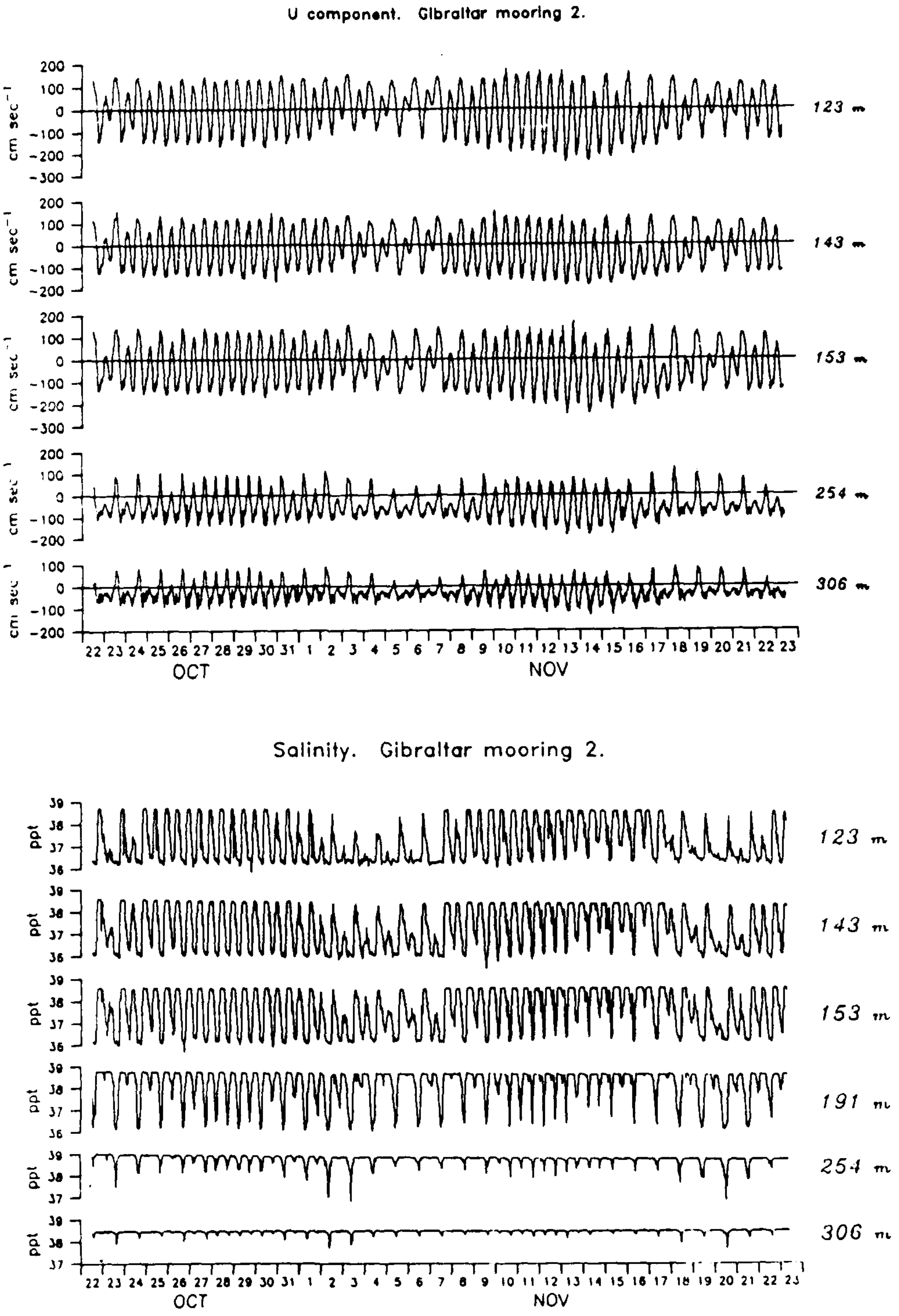


Figure 2: Eastward velocity and salinity at the sill of the Strait of Gibraltar during October-November 1985.

CHLOROFLUOROCARBON ("Freon") STUDIES DURING THE GIBRALTAR EXPERIMENT

J. L. Bullister

The concentrations of the two chlorofluorocarbons (CCl_3F and CCl_2F_2) measured in this study have increased rapidly in the atmosphere since 1930, and these increases can be modeled as a function of latitude and time. These gases cross the air-sea interface, and dissolve in surface seawater. The equilibrium concentrations of these compounds in the mixed layer of the ocean is determined by the concentrations in the overlying atmosphere, and the temperature and salinity of the seawater. The transport of these anthropogenic gases from the surface layer into the interior of the ocean can be used to study sub-surface mixing and circulation processes.

Chlorofluorocarbon measurements were made on approximately 325 water samples collected at 52 stations during the hydrographic survey on the Lynch in September-October 1986. Sample profiles of dissolved chlorofluorocarbon concentrations obtained in the Alboran Sea and Gulf of Cadiz are shown in Figs. 1 and 2. Measurements of the distribution of these compounds in the Alboran Sea will be used to estimate renewal rates of deep waters in the western Mediterranean, and to determine the rates of transport of intermediate and deep waters from their source regions to the sill at Gibraltar. Measurements in the Gulf of Cadiz will be used to determine the contributions of the outflowing Mediterranean water and entrained Atlantic waters to the chlorofluorocarbon signal observed at mid-depths in the North Atlantic.

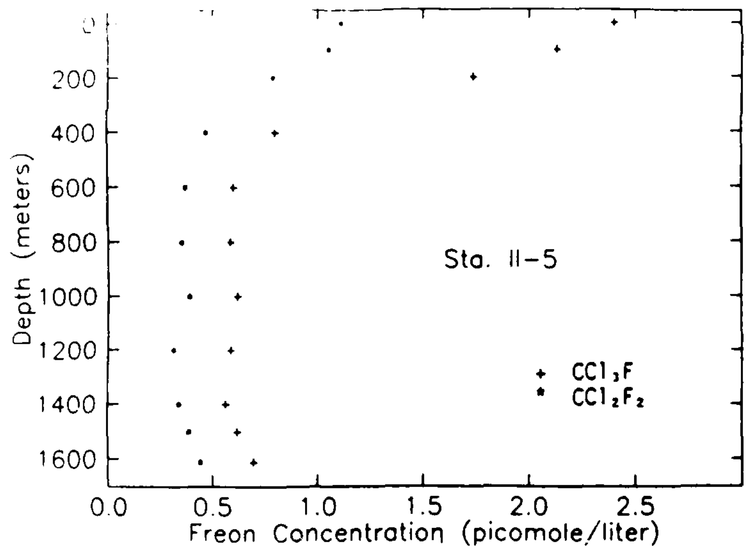


Fig. 1. Profiles of dissolved CCl_3F (Freon-11) and CCl_2F_2 (Freon-12) concentrations (1 picomole=1 X 10^{-12} mole) at Station II-5 in the Alboran Sea. Highest concentrations of dissolved chlorofluorocarbons are found in surface water, which is in contact with the modern atmosphere. The penetration of these anthropogenic compounds through the water column can be used to model renewal rates for the intermediate and deep waters of this region.

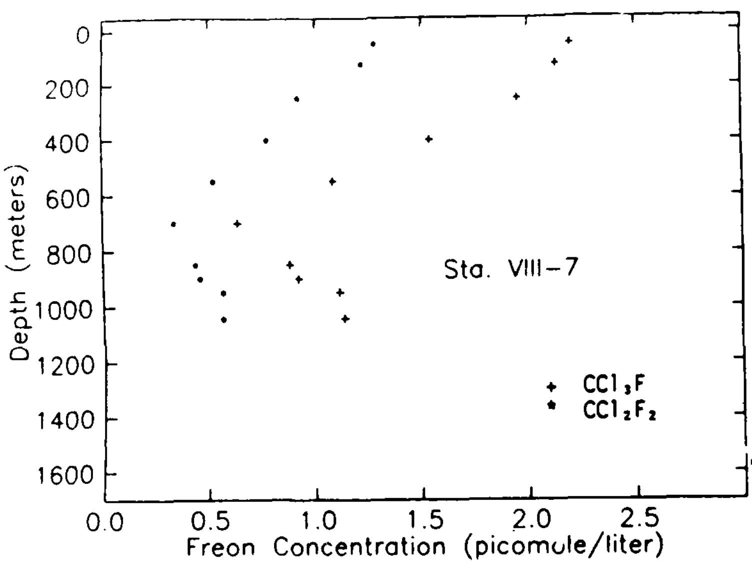


Fig. 2. Profiles of CCl_3F and CCl_2F_2 at Sta. VIII-7 in the Gulf of Cadiz. A strong chlorofluorocarbon signal is carried in the near-bottom, high salinity Mediterranean outflow water in this region.

METEOROLOGICAL OBSERVATIONS IN THE STRAIT OF GIBRALTAR

C. E. Dorman

Atmospheric measurements were made in July and August, 1986 with the goal of understanding what causes the strong easterly winds (Levanters) that occur in the Strait. In this case, we are referring to the small scale Levanters that occur about once every week or 10 days in the summer and are restricted to within 100 km of the Strait. In contrast, the large scale Levanters, which extend from the central Mediterranean to well into the Atlantic, are caused by a large scale synoptic pressure gradient.

To measure the surface winds and pressure in the Strait, an automated weather station was placed on the Spanish ferry La Ciudad de Zaragosa. This ferry takes about two hours to travel between Algeciras and Tangier (Fig. 1). A total of 17 trips were sampled.

Atmospheric soundings were made of the lower atmosphere by free balloons with airsondes. On two Levanters, soundings were made at Tarifa and 25 km to the west on the beach at Zahara de los Atunes. Five airsondes were released on each of two Levanters on the east-bound leg of the ferry.

A typical east-bound ferry crossing during a Levanter is shown in Figure 2, where Tangier is on the left hand side. On this leg, the fastest winds were 25 m/s which was near the lowest surface pressure at the Pt. Malabata Buoy. In all Levanters, the lowest pressure was off Tangier. Pressure differences during the Levanters along the 42 km open channel were between 0.8 and 5.5 mb. The wind speeds were also greatest to the west of Tarifa, with the maximum speed being off Pt. Malabata. Maximum speeds were between 10 and 33 m/s.

These winds and pressures are in conflict with the accepted theory that the Levanters are a "Venturi" effect. If this were true, then the lowest pressures and highest winds would be at the narrowest portion of the Strait which is between Tarifa and Algeciras. Instead, the lowest pressures and highest winds are well to the west, where the Strait is a factor of two wider.

The soundings on the shore and the ferry reveal that the lower kilometer of the atmosphere is increasingly warmer to the west of the narrows. Figure 3 shows the air temperature and dew point from the surface to 1.75 km taken from the ferry during a Levanter. Sounding 14 (solid line) was taken on the east side of the Strait near Pt. Carnero. Sounding 11 (dashed line) was taken near Pt. Malabata, while sounding 12 was off Tarifa. Sounding 11 is substantially warmer than 14, with 12 in between. Presumably, this warming is due to weak subsidence on the lee side of the mountains on either side of the Strait. Weak easterly winds up to 1.5 km accompany Levanters.

This suggests a cause for the Levanters. Weak easterly winds subside and warm the lower atmosphere on the west side of the Strait and decrease the surface pressure by a few millibars. The pressure field accelerates the surface winds, causing the highest velocities off Tangier.

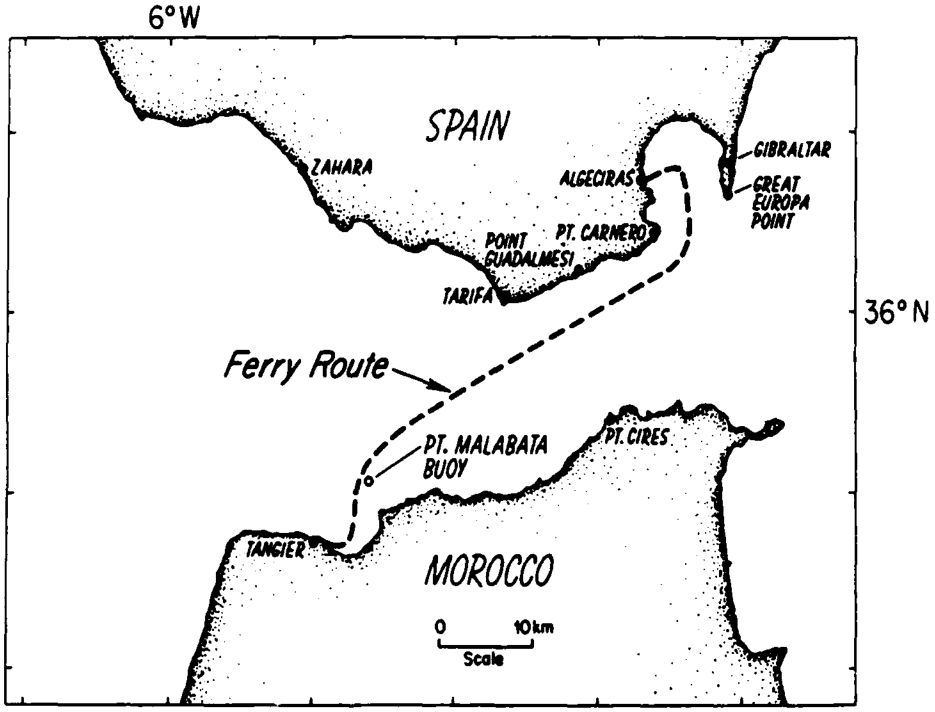


Figure 1. Meteorological observations were taken along the ferry route between Tangier and Algeciras.

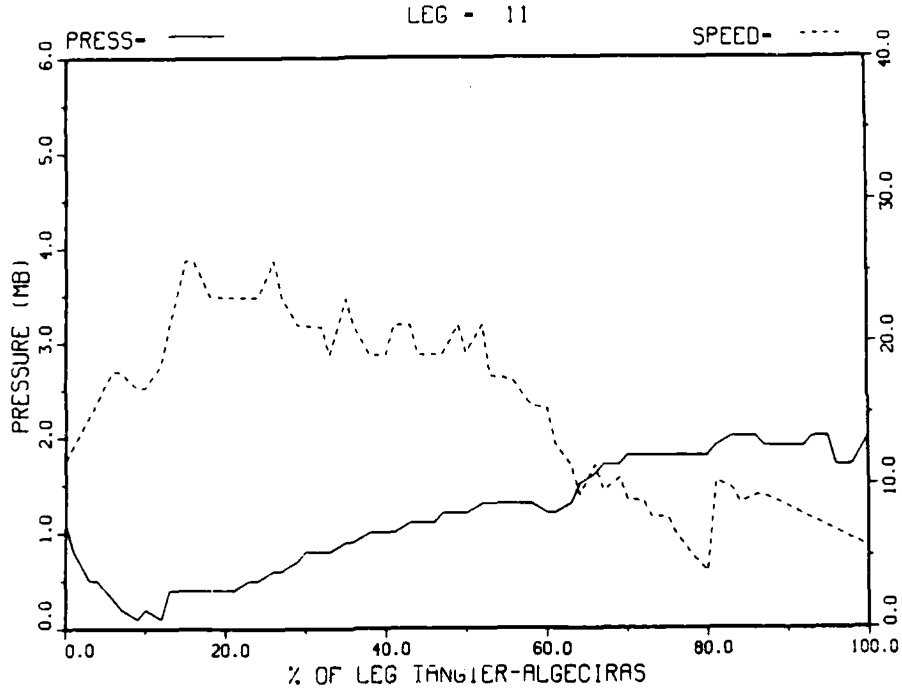


Figure 2. Surface pressure (minus 1011 mb) and surface wind vs. the ferry route from Tangier (left side) to Algeciras (right side). Turning into Algeciras bay causes the perturbations to the right of the 80% point.

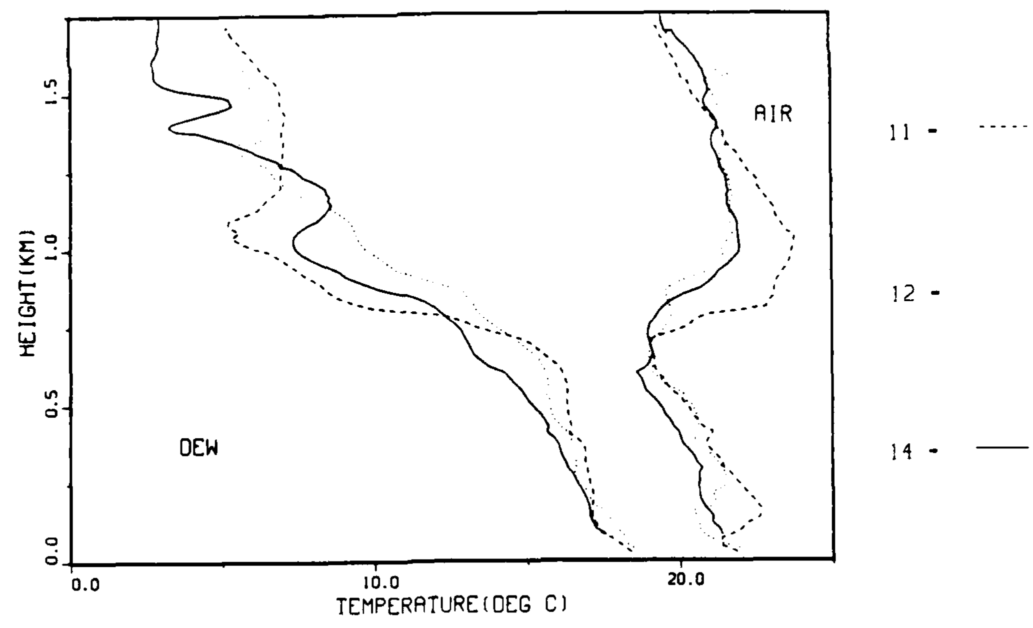


Figure 3. Atmospheric soundings taken from the ferry during a Levanter. Sounding 11 is near Pt. Malabata, sounding 12 is off Tarifa, and sounding 14 is off Pt. Carnero on the east side. Warming to the west causes the lower surface pressure and high winds to the west of the narrows.

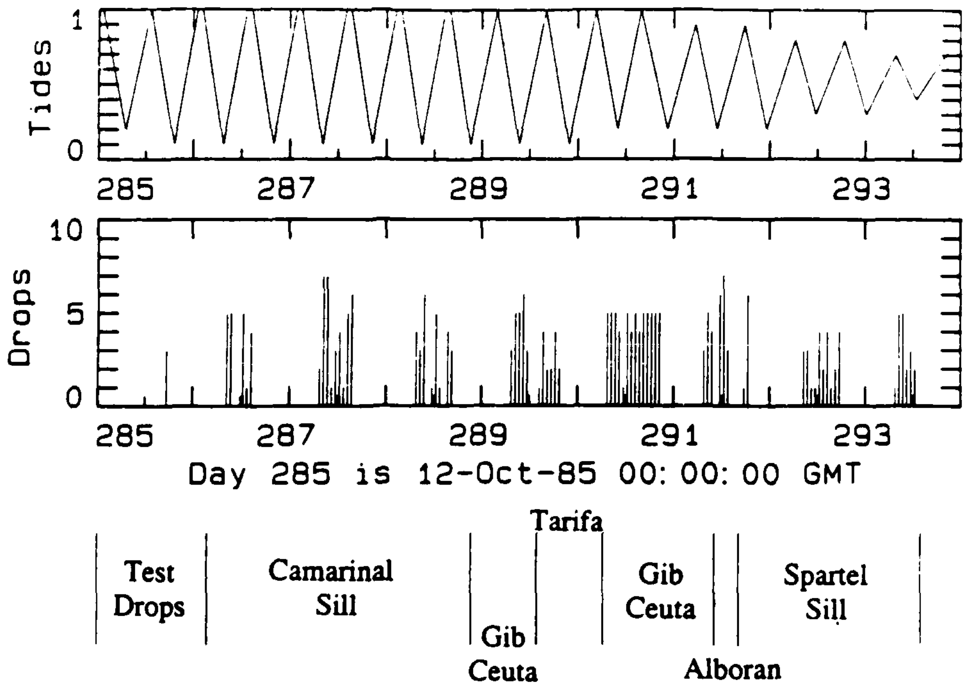
ADVANCED MICROSTRUCTURE PROFILER (AMP) CRUISE SUMMARY -- STRAIT OF GIBRALTAR CRUISES

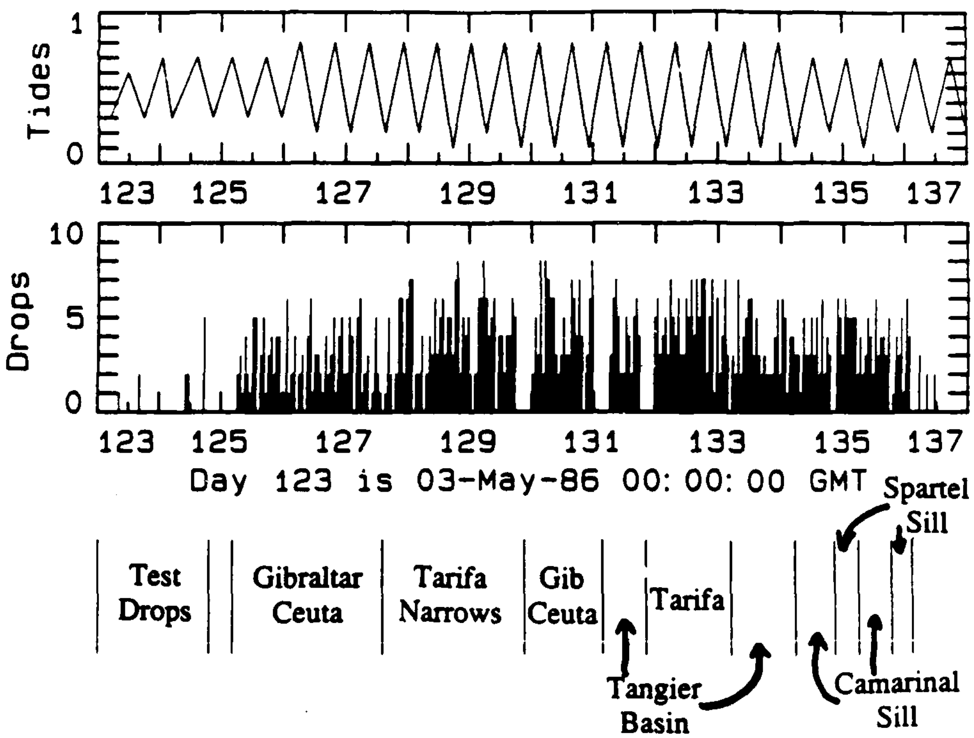
M. Gregg, W. Nodland and J. Wesson

The two AMP group cruises were in October 1985 and May 1986. During the first cruise we operated AMP only during the day and made about 275 AMP profiles. In the second cruise we operated AMP around the clock and made over 1000 drops in a two week period. During both cruises we also operated a high-frequency acoustic backscatter sonar provided by D. Farmer, and an Acoustic Doppler Current Profiler. The combination of AMP profiles with acoustic profiling was found to be highly effective. The confirmation and intercomparison of observations made by two or more instruments is quite pleasing. For instance, observations of high dissipation rates were confirmed by the appearance of billows and chaotic structures in the acoustic backscatter images as well as the appearance of high shear in the Doppler profiler data.

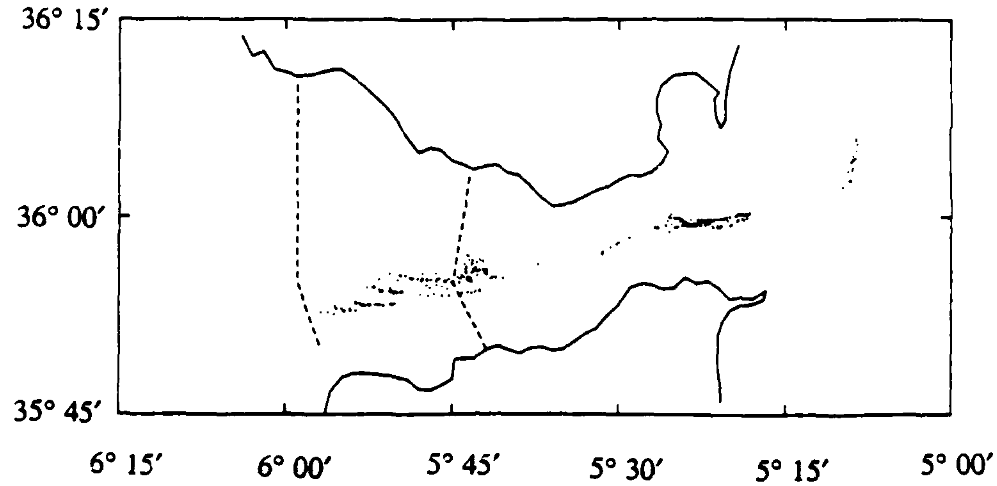
The first four accompanying figures show where AMP profiles were taken, in time and space. The sampling is not as good as it may be hoped, but the AMP profiling operation was constrained by various factors beyond our control. Ship traffic made it unwise to lie-to anywhere but in the separation zone along the center of the Strait. Winds, when the Levante was blowing, were strong enough to make operations, especially at night, difficult or impossible. We were forced to move from one end of the Strait to the other on some occasions. Finally, fishing boats often made operations near either sill impossible on some occasions, in which case we moved operations to less popular locations. This problem was worst at night.

There are three areas of particular interest in the data we have taken. The first is the behavior of the two-layer flow over Camarinal Sill. The mixing is very vigorous and the spreading of the interface west of the sill as Mediterranean water appears to pass through a hydraulic jump is observed both with the AMP profiles and with the acoustic backscatter sonar. The second area of interest is the passage of an internal soliton along the Strait. The soliton is released near high water and flows toward the Mediterranean as a wave of depression of the interface between the upper and lower layers. The third area of interest is the intercomparison between the mean interface depths for the two cruises. There is clearly a difference in the thickness of the upper layer in the eastern end of the Strait for the two cruises. In the October cruise, the upper layer appears to be much thicker than during the May cruise. The accompanying figures illustrate some preliminary results of these analyses.

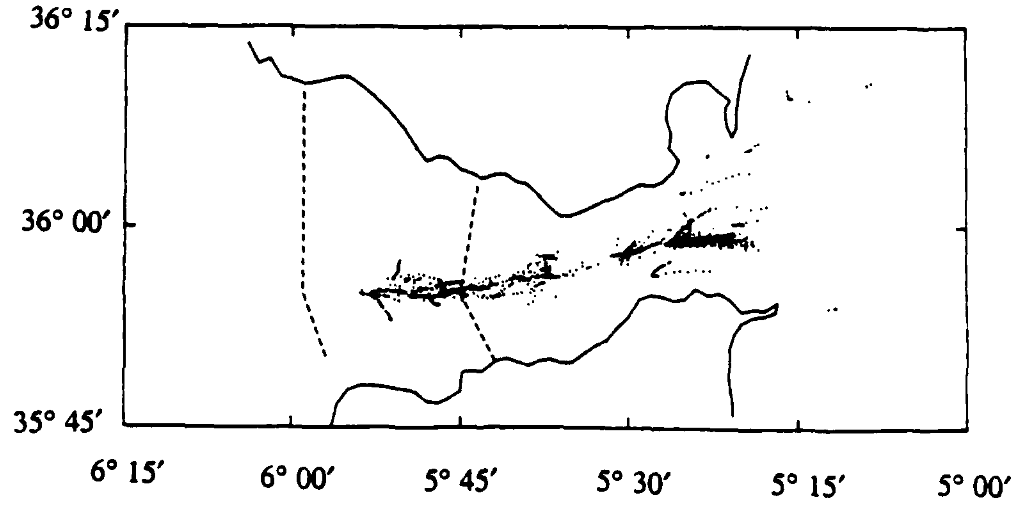

Tides
Drops
Day 285 is 12-Oct-85 00:00:00 GMT
Test Drops
Camarinal Sill
Gib Ceuta
Tarifa
Gib Ceuta
Alboran
Spartel Sill

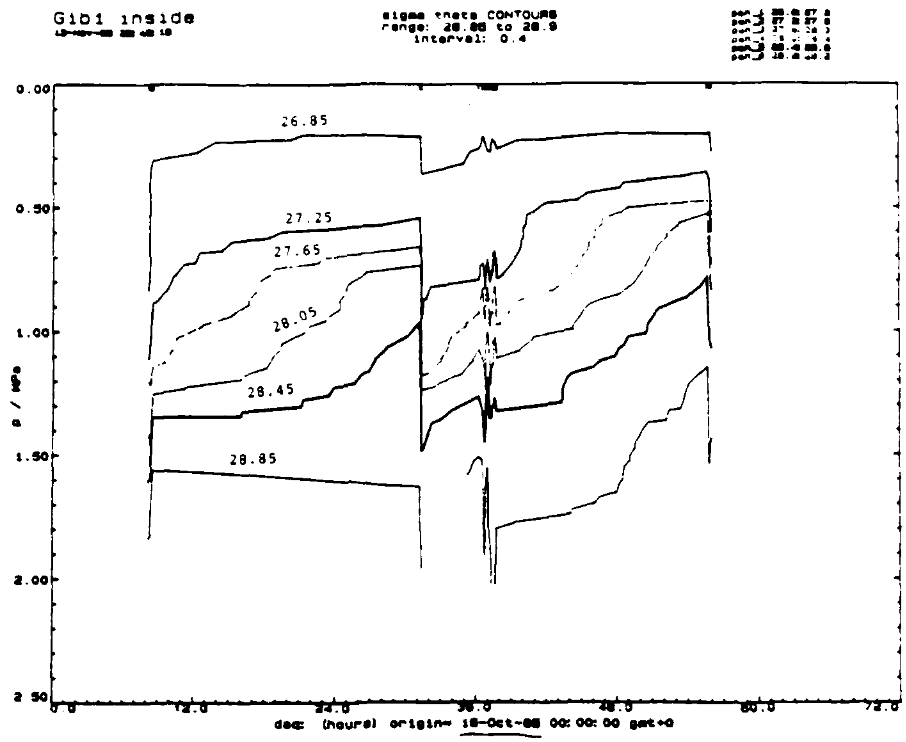

Tides
Drops
Day 123 is 03-May-86 00:00:00 GMT
Test Drops
Gibraltar Ceuta
Tarifa Narrows
Gib Ceuta
Tarifa
Tangier Basin
Spartel Sill
Camarinal Sill

Gibraltar 1 AMP Drops
October 12-20, 1985

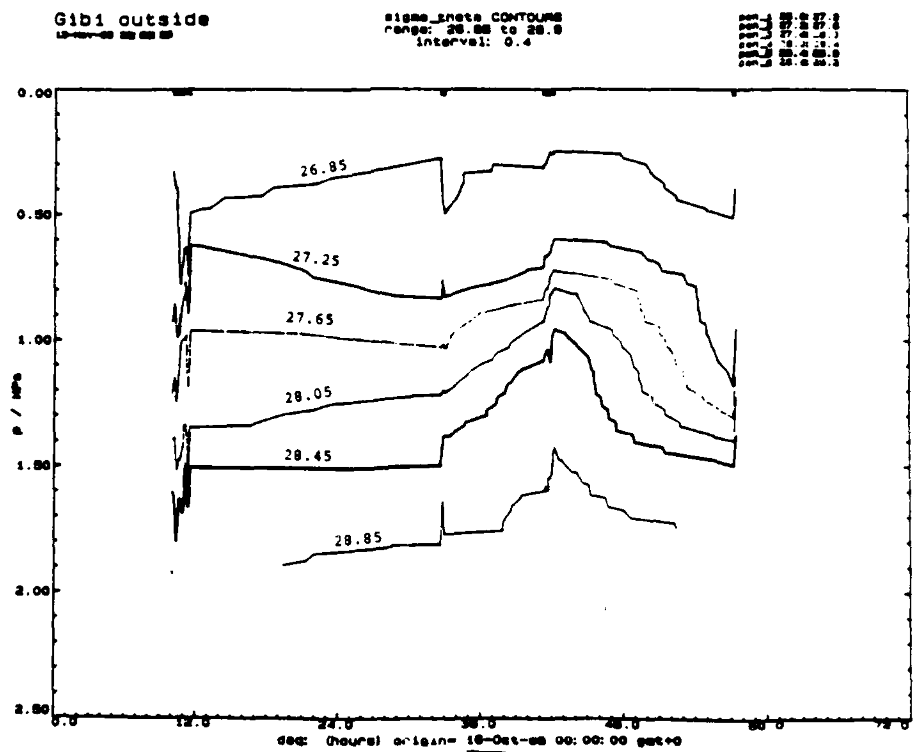


Gibraltar 2 AMP Drops
May 3-16, 1986

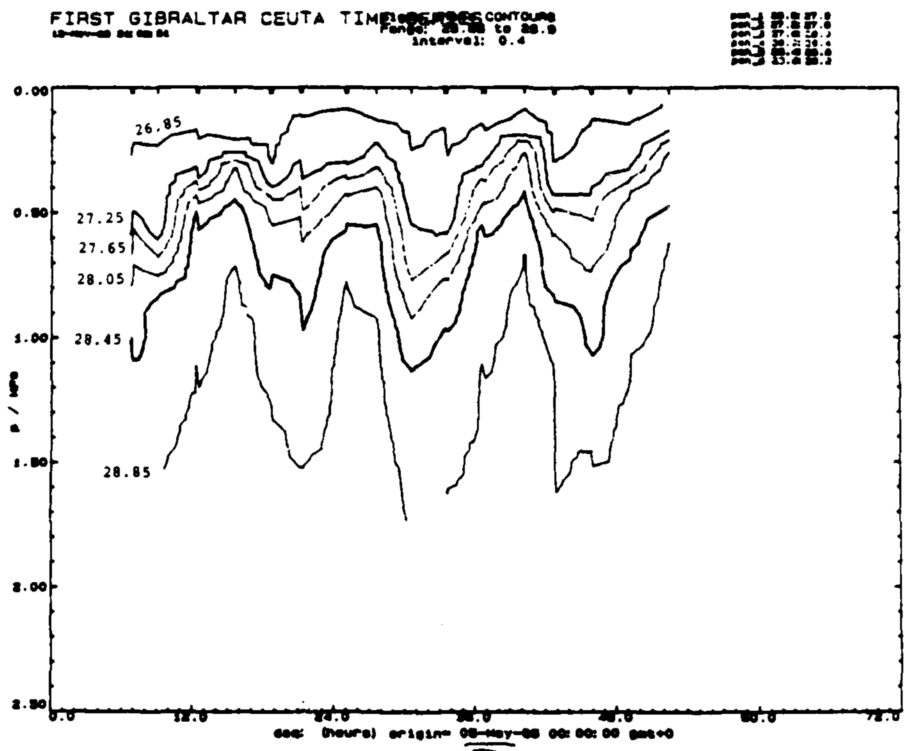




AMP Drops between 5°24' and 5°25.5' W -- mid-strait

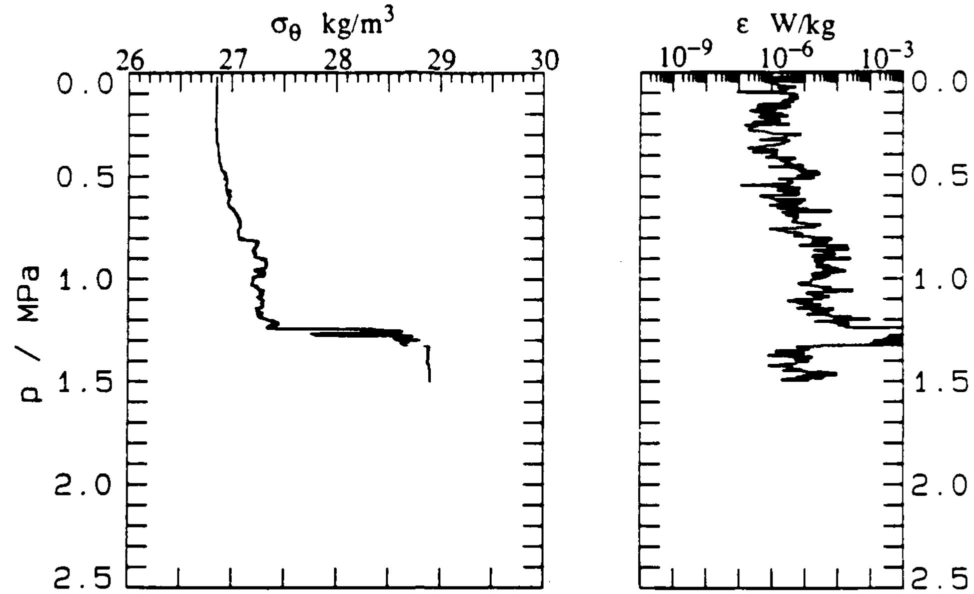


AMP drops between 5°22' and 5°20' W -- mid-strait

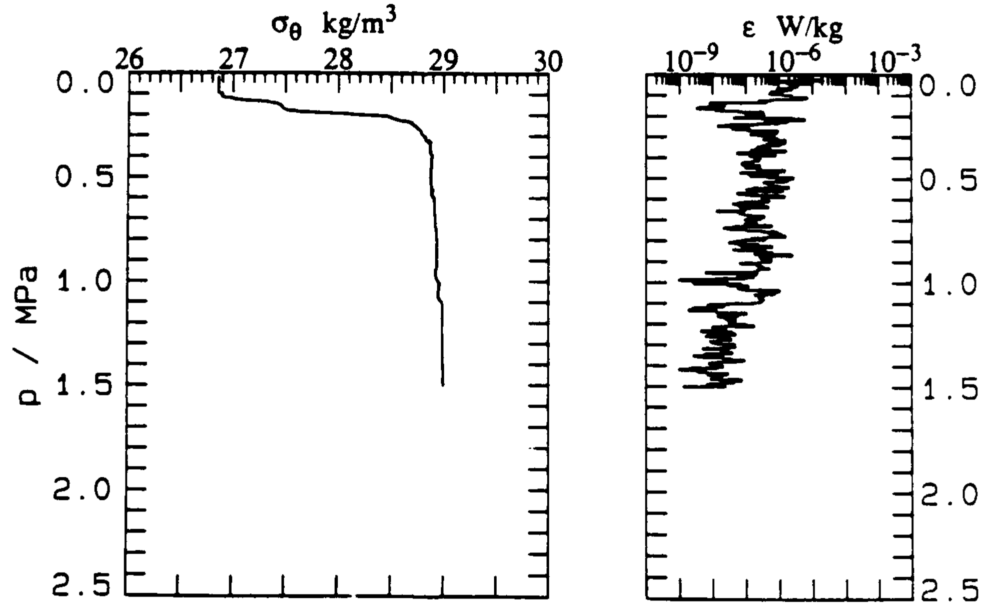


AMP Drops between 5°24' and 5°25.5' W -- mid-strait

AFTER THE BORE
09-May-86 04: 20: 30



BEFORE THE BORE
09-May-86 04: 13: 40



METEOROLOGICAL MEASUREMENTS DURING THE WESTERN MEDITERRANEAN CIRCULATION EXPERIMENT

J. Haggerty and R. Fett

1. Introduction

During the winter and spring of 1986, meteorological data were collected by the Naval Environmental Prediction Research Facility (NEPRF) in conjunction with the Western Mediterranean Circulation Experiment (WMCE). The primary purpose of this effort was to obtain in-situ atmospheric measurements of visibility and related variables for comparison with corresponding satellite measurements. This report will describe the data set and briefly discuss applications of the data.

2. Data Summary

Table 1 provides a summary of the data set including dates, general locations and variables measured during the period. Specific features of each element of the data set are given below:

a) Vertical profiles

High resolution soundings of pressure, temperature and dewpoint temperature were made on all of the dates listed in Table 1. Twice daily soundings were taken onboard the USNS Lynch for the period of June 16-30, 1986. At least one sounding per day was taken on all of the remaining days. The soundings are available on floppy disc or magnetic tapes and have been plotted on skew T-log P diagrams.

b) Surface observations

Hourly observations of surface meteorological variables were taken during daylight hours from the USNS Lynch (June 16-30) and the USS America (June 19-27). The observations include pressure, temperature, dewpoint temperature, wind speed and direction, cloud cover and present weather.

c) Aerosols

Extensive measurements of atmospheric aerosols were made onboard the USNS Lynch during June 16-30. The measurements include aerosol size distribution (0.0025 to 5.0 microns), scattering coefficient (visibility), and sun photometer readings of solar intensity (aerosol optical depth) at hourly intervals during daytime. Particle samples for composition analysis and large droplet distribution measurements were taken approximately 2-3 times per day.

Certain aerosol measurements were also taken on the USS America (June 17- 29). These include scattering coefficient, solar intensity, and occasional particle samples.

d) Satellite data

Since the time of the experiment, the following satellite data have been acquired:

DMSP visible and IR images
TOVS fields of temperature and precipitable water
Meteosat visible and IR images (available on a film loop)
AVHRR channel data (on order through NORDA)

The DMSP, TOVS and AVHRR data cover all the dates listed in Table 1; the Meteosat data covers the period of May 28-July 3.

3. Data reduction and analysis

Surface and upper air synoptic charts have been obtained for the experimental period and are being analyzed in conjunction with the satellite imagery. Sounding data have been reviewed and plotted. Measurements of scattering coefficient have been converted to visibility and aerosol optical depth has been derived from about half of the available sun photometer readings. Drop samples and particle counts are currently being analyzed.

4. Applications

A comparison of visibility measurements with visibility calculations from the Navy Aerosol Model is currently in progress. Preliminary results show substantial errors which illustrate the difficulty in using an aerosol model in a region with a variety of aerosol sources such as the Mediterranean. Further comparisons using a model which calculates visibility from satellites will be performed when the AVHRR data is received.

Other planned uses of the data include support of gray shade analysis in DMSP imagery and verification of a scheme to improve marine boundary layer model forecasts with satellite soundings.

Table 1: Summary of Meteorological Measurements during the Western Mediterranean Circulation Experiment

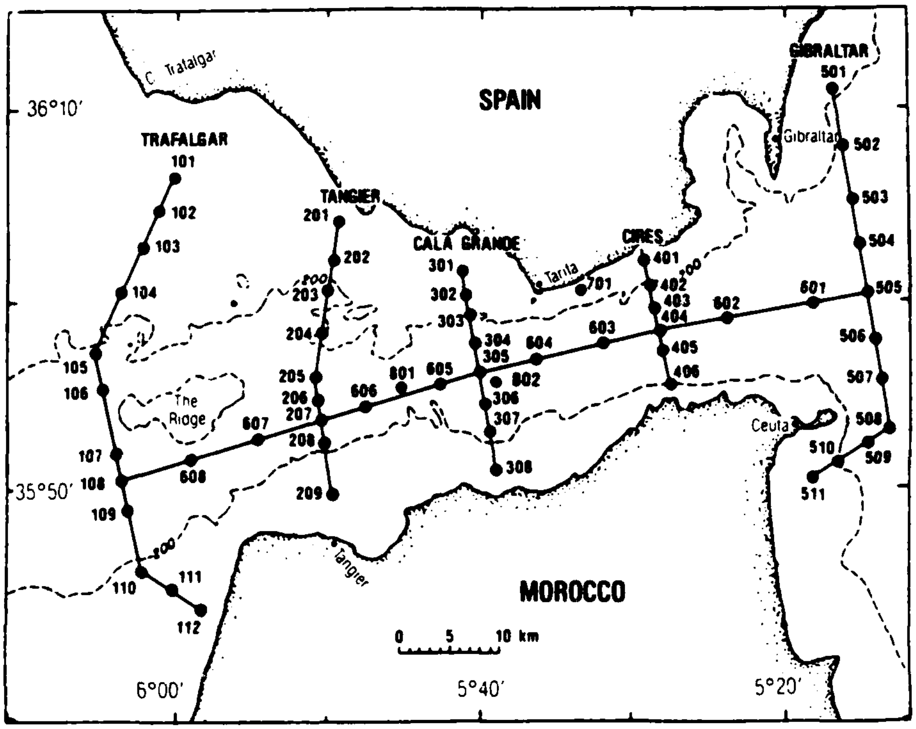
Dates	Location	Data
24 Feb - 15 Mar	Straits of Sicily (oil platform)	P, T, T_d soundings
27 May - 13 Jun	Rota - Alboran Sea (USNS *Lynch*)	P, T, T_d soundings
16 Jun - 30 Jun	Rota - Strait of Gibraltar (USNS *Lynch*)	soundings, hourly surface observations, aerosols, visibility
19 Jun - 27 Jun	Palma - Naples (USS *America*)	soundings, hourly surface observations, aerosols, visibility
28 Jun - 14 Jul	Naples - Renidorm (USS *America*)	soundings

HYDROGRAPHIC STRUCTURE OF THE STRAIT OF GIBRALTAR

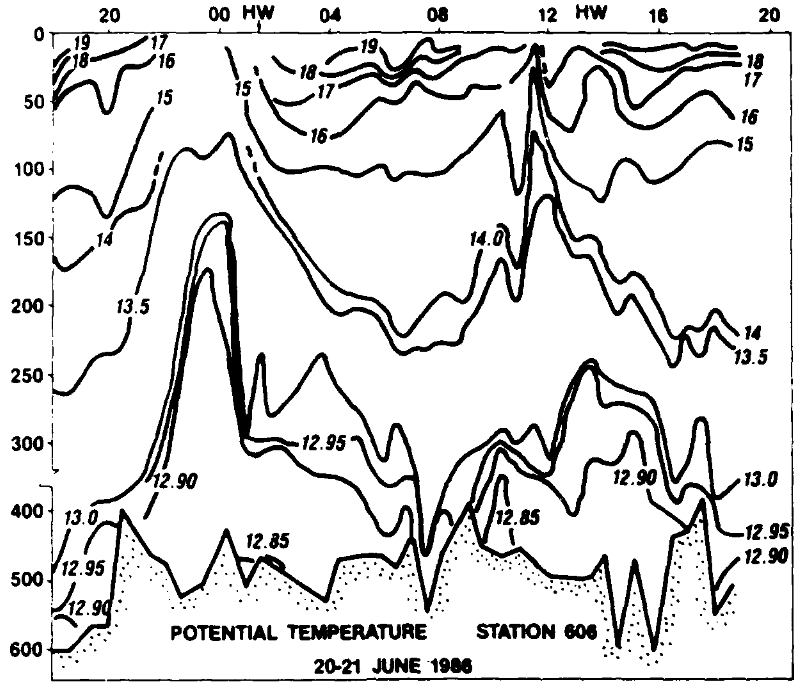
T. H. Kinder, G. Parrilla and D. A. Burns

The central objective of this project is to define the hydrographic structure of the Strait over tidal time scales from fortnightly to semi-diurnal. Two cruises on the Lynch were dedicated to this objective: 1-17 November 1985 and 17-29 June 1986. Additional cruises by Bray during spring and fall 1986 added important complementary data.

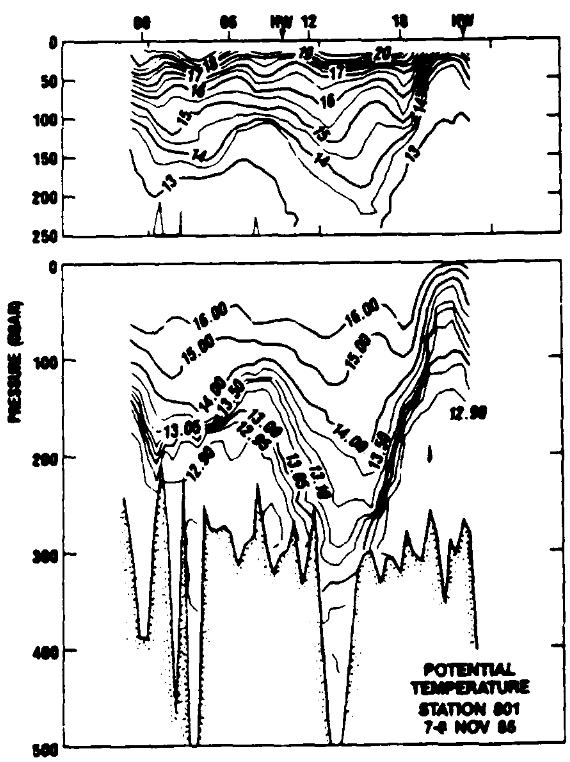
The November 1985 cruise (317 casts) was dedicated to defining the cross-strait structure, especially at diurnal and spring/neap frequencies. Lynch repeated the five cross-strait sections (Fig. 1) during subsequent diurnal tides at both springs and neaps (i.e., each section was done four times). A 25-hour time series station was done near the sill (801) and rapid repeated occupations of the Cires section were done through one diurnal cycle during both springs and neaps. During the June 1986 cruise (319 casts), diplomatic problems forced the ship to remain in the southern half of the Strait. Long (24 or 48 hour) time series were occupied (stations 606 and 802) at both springs and neaps. During SAR overflights by Richez a series of stations was taken for comparison with the radar data.



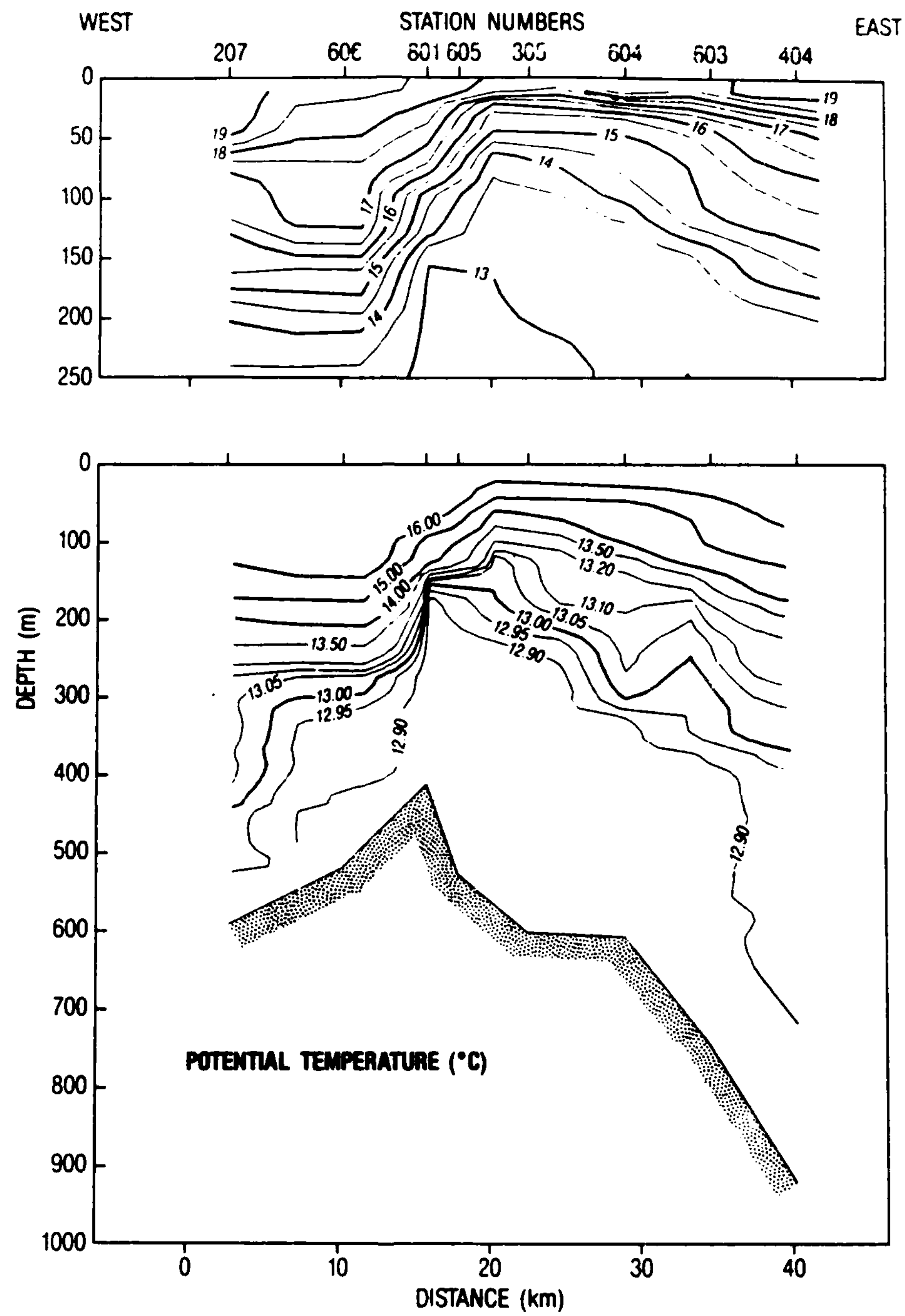
The station grid. The sill is located between stations 606 and 801. The five cross-strait sections begin with the numerals 1 (Trafalgar) through 5 (Gibraltar).



Time series station west of the sill (station 606) during spring tides. During this 25-hour long station 50 CTD casts were made. The Western Mediterranean Deep Water (WMDW) is delineated by potential temperatures less than 12.90°C.



Time series station east of the sill (station 801) during neap tides. During this 25-hour-long station 50 CTD casts were made. The 12.90°C potential isotherm delineates WMDW.



An along-strait section made on 17 November 1985 between spring and neap tides. The actual sill is between stations 801 and 606 at less than 300 m depth. The 12.90°C potential isotherm delineates the WMDW.

TRACE ELEMENTS

C. Measures

Two profiles each consisting of 15 samples were collected during the recovery phase of the Gibraltar Experiment. The stations, which were located at 35 50.2 N, 4 44.3 W and 35 48.1 N, 6 15.1 W on October 13th and 15th respectively, were analysed for Aluminium and Selenium on board ship. Stored samples for shore-based determination of stable Beryllium 9 and cosmogenically produced Beryllium 10 were also obtained. The observed levels of Al in the Alboran Sea are the highest seen in any ocean; this is consistent with both the recent ventilation of the deep Alboran and the large aeolian input to the regions of deep water formation.

Aluminium concentrations of 109 nM in the Western Mediterranean Deep Water are higher than the 86 nM value of the Levantine Intermediate Water. This may be a consequence of either the more recent ventilation of the former or the location of its formation region with respect to aeolian inputs. Preliminary interpretation of the Aluminium data shows that the Mediterranean outflow, if salt balanced for 13% entrainment of inflowing Atlantic water, yields Al values that are only satisfied if the remaining deep water outflow is composed entirely of Levantine Intermediate Water with no contribution from the Western Mediterranean Deep Water.

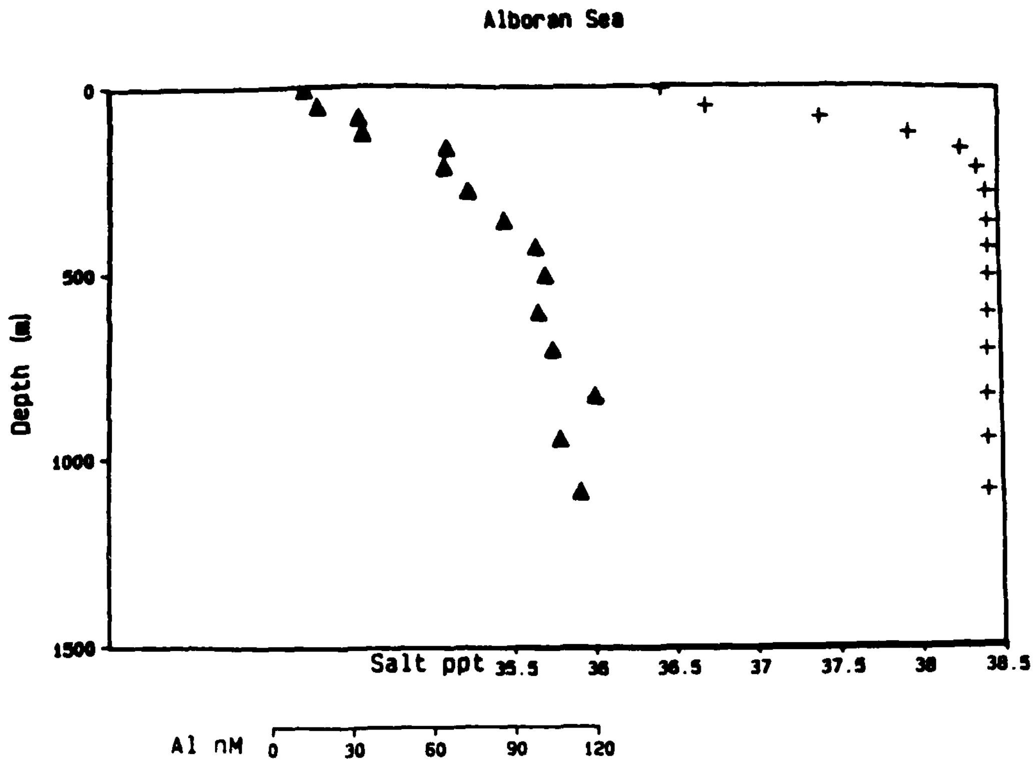
Shore-based analyses for the two isotopes of Beryllium will be undertaken to determine whether or not the Mediterranean is the source of elevated values of this ratio observed recently in the North Atlantic.

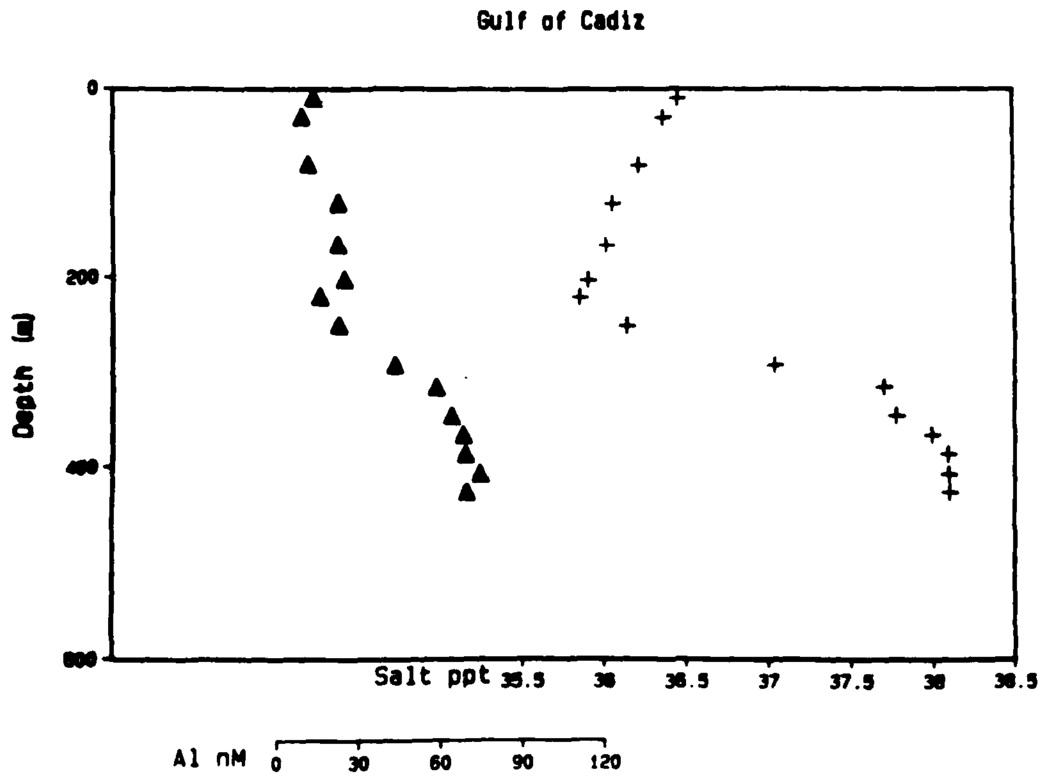
STATION 1

I/D #	SAMP .#..	DEPTH (M)	TEMP	SALT PPT	..Al.. ..nM..	SeIV pM	SeVI pM	T.Se pM
1	1312	9	20.479	36.411	12.30	211	1263	1474
2	1317	54	15.013	36.686	17.20	178	1532	1710
3	1305	84	14.186	37.387	32.30	289	1244	1533
4	1314	124	13.460	37.938	33.80	317	1496	1813
5	1313	164	13.086	38.266	65.00	399	1471	1870
6	1212	214	13.045	38.368	64.00	420	1539	1959
7	1217	279	13.069	38.424	73.00	329	1645	1974
8	1205	359	13.019	38.428	86.20	425		
9	1214	429	13.001	38.430	98.10	455	1503	1958
10	1213	505	12.975	38.424	101.50	453	1355	1808
11	1112	607	12.947	38.418	99.00	513	1507	2020
12	1117	707	12.928	38.411	104.20	561		
13	1105	827	12.928	38.408	120.00	495	1515	2010
14	1114	944	12.933	38.408	106.80	557	1444	2001
15	1113	1083	12.942	38.406	114.50	575	1477	2052

STATION 2

I/D #	SAMP .#..	DEPTH (M)	TEMP	SALT PPT	..Al.. ..nM..	SeIV pM	SeVI pM	T.Se pM
1	2312	10	20.350	36.452	13.30	129	1264	1393
2	2317	30	17.930	36.362	8.90	64	1356	1420
3	2305	80	15.659	36.210	11.20	93	1314	1407
4	2314	120	14.760	36.052	22.50	137	1535	1672
5	2313	164	14.522	36.011	22.40	166	1672	1838
6	2212	201	13.895	35.899	24.60	225	1469	1694
7	2217	219	13.597	35.849	15.80	209	1757	1966
8	2205	249	13.554	36.137	22.70	251	1547	1798
9	2214	291	13.815	37.044	43.20	254	1579	1833
10	2213	314	13.552	37.701	58.30	355	1560	1915
11	2112	344	13.506	37.778	64.10	328	1585	1913
12	2117	364	13.355	37.990	68.10	367	1546	1913
13	2105	384	13.284	38.089	69.00	378	1621	1999
14	2114	405	13.284	38.093	74.30	413	1529	1942
15	2113	424	13.284	38.098	69.40	327	1682	2009


Alboran Sea
Depth (m)
0
500
1000
1500
Salt ppt 35.5 36 36.5 37 37.5 38 38.5
Al nM 0 30 60 90 120


Gulf of Cadiz
Depth (m)
0
200
400
600
Salt ppt 35.5 36 36.5 37 37.5 38 38.5
Al nM 0 30 60 90 120

NUMERICAL MODELING OF A TWO-LAYERED FLOW THROUGH THE STRAIT OF GIBRALTAR

D. Ouazar, N. Benmansour and C. A. Brebbia

Objectives

The main objectives of this research are as follows (1, 3, 5):

- Location of the mean interface between the Atlantic and Mediterranean layers.
- Study of internal waves.
- Estimation of the exchanges between the Atlantic and Mediterranean basins.
- Determination of the temporal variability on the exchanges and on the interface.
- Comparison of the numerical results to experimental values.

Formulation and Proposed Method of Solution (one-dimensional flows)

The model described herein uses the momentum and mass conservation equations to simulate a one-dimensional unsteady state two-layered flow. The resulting hyperbolic set of partial differential equations can be solved by using an appropriate numerical method. Some preliminary results have already been obtained by the characteristic method (1, 5). The hydrodynamic equations used in this model are the depth-integrated shallow water equations for the two layers:

$$\partial h/\partial t + \partial(u_1 h_1)/\partial x = 0$$

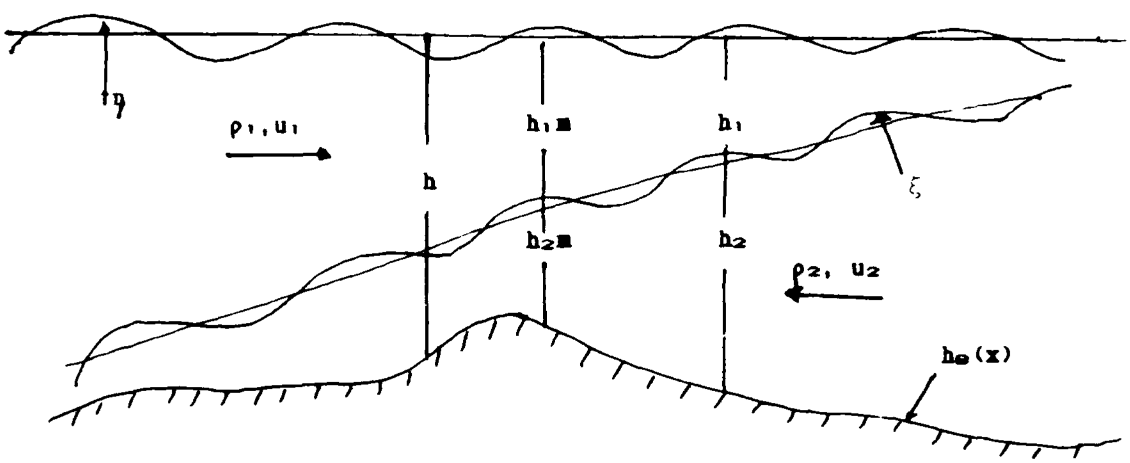
$$\partial u_1/\partial t + u_1(\partial u_1/\partial x) + g(\partial h/\partial x) + C_{DI}/h_1\ (u_1-u_2)|u_1-u_2| - Ax/h_1 = 0$$

$$\partial h_2/\partial t + \partial(u_2 h_2)/\partial x = 0$$

$$\partial u_2/\partial t + u_2(\partial u_2/\partial x) + g(\rho_1/\rho_2) + g(\partial h_1/\partial x) + \partial h_2/\partial x\ C_{DI}/h_2(u_2-u_1)|u_1 u_2|$$
$$- (C_{DB}/h^2)u_2^2 = 0$$

Here, the following definitions hold:

u_i = mean velocity in the layer i
h_i = instantaneous depth of the layer i
η, ζ = perturbation layer depths
C_{DI} = dimensionless drag coefficient at the interface
C_{DB} = bottom friction coefficient
Ax = atmospheric wind stress in the (x) direction.



Model of a two-layer flow through the Strait of Gibraltar where $h_1 = h_{1m} + \eta - \xi$, $h_2 = h_{2m} + \xi$, $h = h_1 + h_2$

In a preliminary simplified model elaborated by some researchers at Ecole Mohammadia d'Ingenieurs (1, 5), the free surface was supposed to be rigid and effects of friction and rotation were neglected. The hydrodynamic equations obtained were integrated numerically using the characteristic method. Comparisons with experimental results showed a surprisingly close agreement for the interface. Moreover, as predicted by Lacombe, the model detected a moving hydraulic jump of 50 meters height and 3 hours period at the sill. This research is being extended by taking into account perturbations at the free surface and frictional effects at the interface and at the bottom. The extended model uses a wave equation formulation reported by Lynch and Gray (4); this formulation seems to provide some numerical advantages. The wave equation for each layer is derived by combining the continuity and the momentum equations. Therefore, two similar equations are obtained for η and ξ:

$$\partial^2/\partial t^2 = (g\varepsilon h_{2m})\partial^2\xi/\partial x^2 + g(1-\varepsilon)\, h_{2m}\, \partial^2\eta/\partial x^2 + \partial^2/\partial x^2\, (h_{2m}\, u_2\, u_2)$$

$$+ C_{DI}\, \partial/\partial x\, [(u_2-u_1)|u_1-u_2|] - C_{DB}\, \partial u_2{}^2/\partial x^2$$

$$\partial^2\xi/\partial t^2 = g(h_m - h_{2m})\, \partial^2\eta/\partial x^2 + g\, h_{2m}\, \partial^2\xi/\partial x^2 - C_{DB}\, \partial u_2{}^2/\partial x^2$$

$$+ \partial^2/\partial x^2(u_1u_1h_1 + u_2u_2h_{2m})$$

The wave equations will be solved in connexion with the momentum equations by the boundary element method. This method, which is the newcomer in computational techniques, offers important advantages over domain type solutions such as finite elements. A solution for a simplified one-dimensional wave equation has been developed in (2). It has shown a promising feature -- The work undertaken, actually, will be based on Boundary and Finite Element techniques coupling. In a first step, one-dimensional flows will be analyzed. The second and last step will be the modeling of the three-dimensional flows, or more properly, the so-called 2.5 D depth-integrated equations.

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ACOUSTIC DOPPLER CURRENT MEASUREMENTS

N. Pettigrew and J. Irish

The experimental objectives of the Doppler current meter program in the Gibraltar experiment are listed below.

Primary objectives:

1) Investigate the long-term flow structure at the Sill and Tarifa Narrows sections, and estimate transport in the Atlantic and Mediterranean layers, and;

2) Obtain detailed measuremnts of the flow structure associated with the internal bore that propagates through the Tarifa Narrows.

Secondary objectives:

1) Investigate in detail the vertical shear between the inflowing Atlantic layer and the outflowing Mediterreanean layer, and;

2) Examine the time series plots of the upper and lower layer Froude numbers at the presumed hydraulic control sections of the Sill and the Tarifa Narrows.

The Doppler array deployed to achieve these objectives is shown in Figure 1. The four bottom-mounted profilers located at Sill North (SN), Sill South (SS), Tarifa North (TN), and Tarifa South (S) were all scheduled to be recovered and reset midway through the 13-month experimental period. The buoy-mounted profiler in the "central" Tarifa Narrows (TC), was planned as a shorter deployment in the second phase of the experiment.

Instrument performance and data return

The performance of the instrumentation systems and the data return are summarized in Table 1. Two of the bottom-mounted profiling systems were lost due to acoustic release failures. In addition, there were several failures of the Sea Data high capacity tape recording systems.

As a consequence of the data losses, we obtained data only in the Tarifa Narrows section of the Strait. Therefore the achievement of primary objective 1 awaits the integration of the Doppler and conventional current meter records. The other three experimental objectives were all successfully accomplished for the Tarifa Narrows section.

Preliminary results

Data from the buoy-mounted Doppler profiler (TC) provide a uniquely detailed picture of the flow structure in the Tarifa Narrows. Figure 2 shows a detailed view of the passage of a velocity "front" associated with the internal bore. The data are taken from a 3-day period near the middle of a spring tide. The acceleration of the flow is remarkably abrupt. At times, the eastward flow component increases by approximately 1 m/s over 5 minutes. Closer examination of the record reveals that the eastward flow acceleration occurs on the falling tide, and that the signature in successively deeper locations is lagged in time and of lesser amplitude. At the approximate mean depth of the interface (80 m) the event occurs at mean tide.

The arrival of the velocity front is accompanied by a rapid deepening of the interface between the Atlantic and Mediterranean waters. By idealizing the Strait as a two-layer fluid, and estimating the layer depths from the depth of the maximum vertical shear, we have calculated time series estimates of internal Froude number for each layer. These results are presented in Figure 3. The lower layer Froude number is always subcritical, while the upper layer alternates between subcritical and supercritical conditions (subcritical on average).

Closer inspection of Figure 3 suggests that during the passage of the bore, the control point moves from a location east of TC to a point west of TC. During this transition, flow at TC goes from subcritical, to critical, to supercritical. With the passing of the internal bore, the flow decelerates, the control moves eastward toward the narrower section, and the flow at TC reverts to subcritical. As the flow further decelerates, hydraulic control is probably lost altogether until the next tidal cycle. These results suggest that in the Strait of Gibraltar, hydraulic control is a fundamentally time dependent process.

Table 1

Bottom-Mounted and Moored

Doppler Profiling Current Meter Measurements

Tarifa North 36 00.1N, 5 33.5W Bottom-mounted Doppler
averaging interval -- 1 hour
8 m vertical averaging (currents)
Water depth -- 165 m

DATA
Bottom temperature -- 10/19/85 - 3/20/86
Bottom pressure -- 10/19/85 - 3/20/86
Currents u,v,w -- 10/19/85 - 12/18/85 (faulty power regulator)
current bins centered at depths of 16 m - 120 m (8 m increments, 14 levels)

Tarifa Center 35 58.4N, 5 32.2W Buoy-mounted Doppler
averaging interval -- 5 minutes
10 m vertical averaging (currents)
water depth -- 650 m
Nominal depth of Doppler float -- 253 m

DATA
Temperature (253 m) -- 3/17/86 - 4/23/86
Conductivity (253 m) -- 3/17/86 - 4/23/86
Pressure (253 m) -- 3/17/86 - 4/23/86
Currents u,v,w -- 3/17/86 - 4/23/86
bins centered at 40-240 m depths, 10 m increment
data at lower depth sporadic -- present only during mooring dip

failures
1st setting
Sill South -- release failure
Sill North -- tape failure
Tarifa South -- tape failure
2nd setting
Sill North -- tape failure
Tarifa North -- release failure

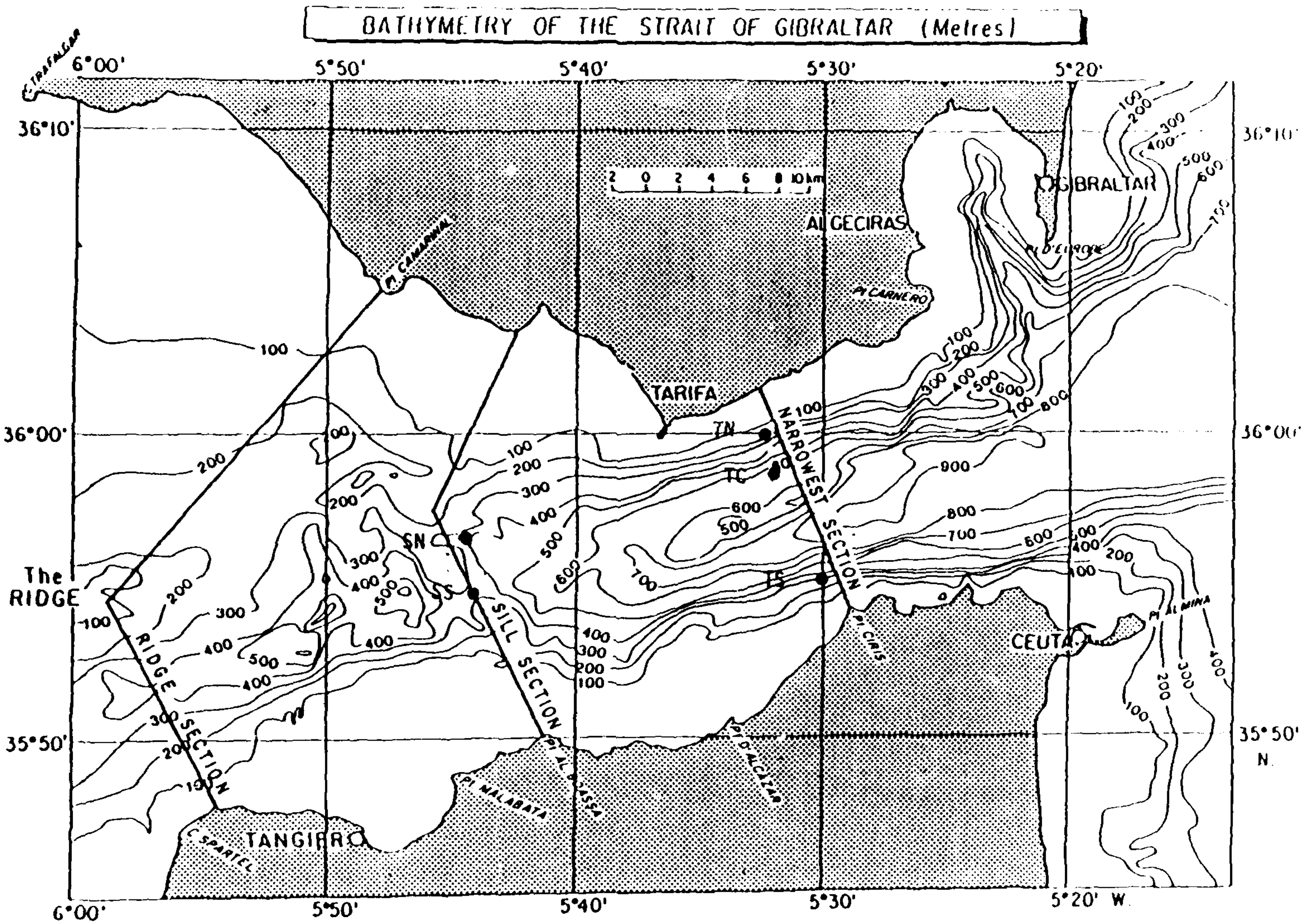

Figure 1. Map showing the locations of moored Doppler Acoustic Profiling Current Meters (DAPCMs) in the Gibraltar Experiment.

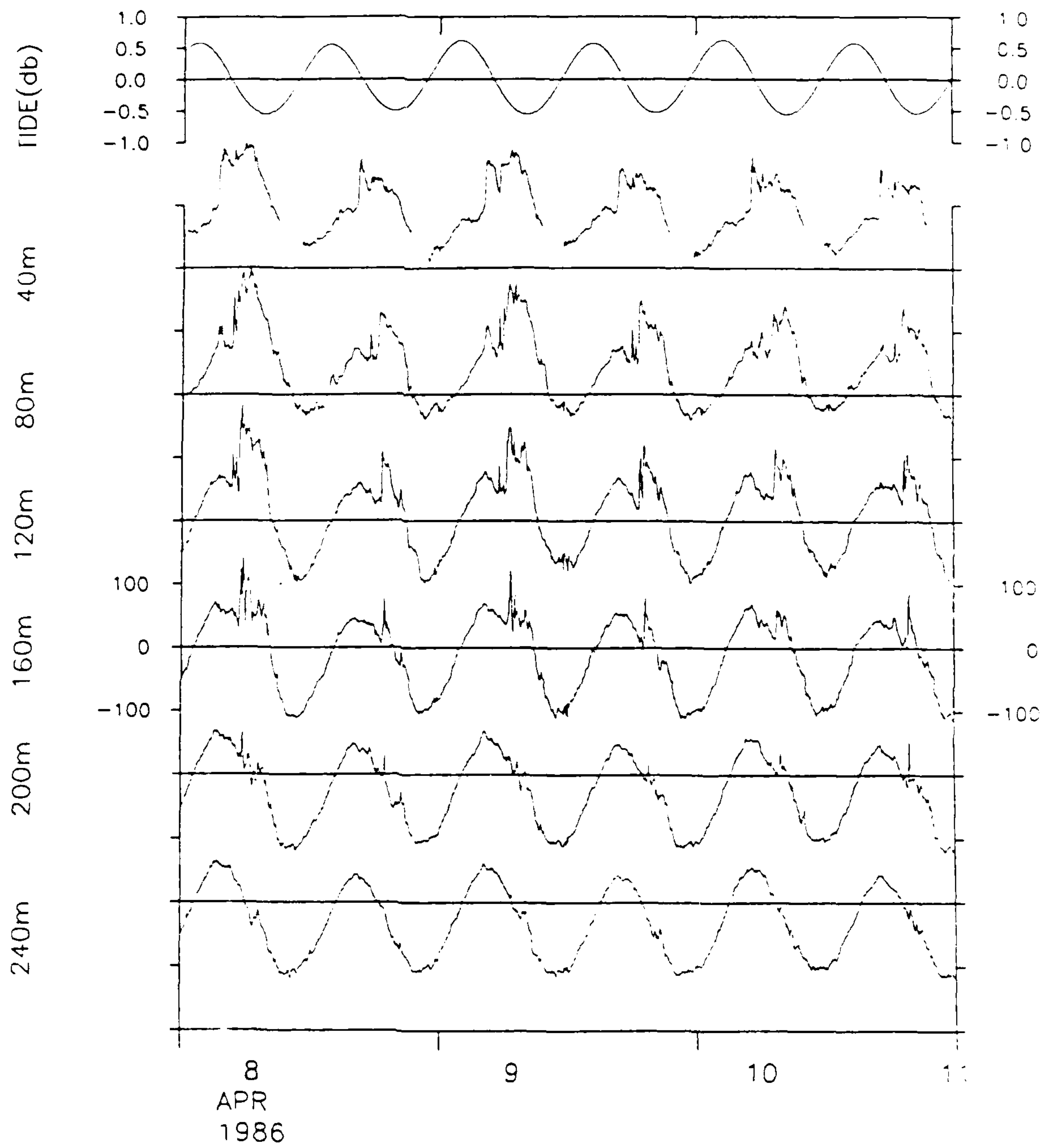

Figure 2. A detailed view of the eastward velocity component during a spring tide. The abrupt eastward accelerations evident at mid-depths are associated with the passage of an internal bore.

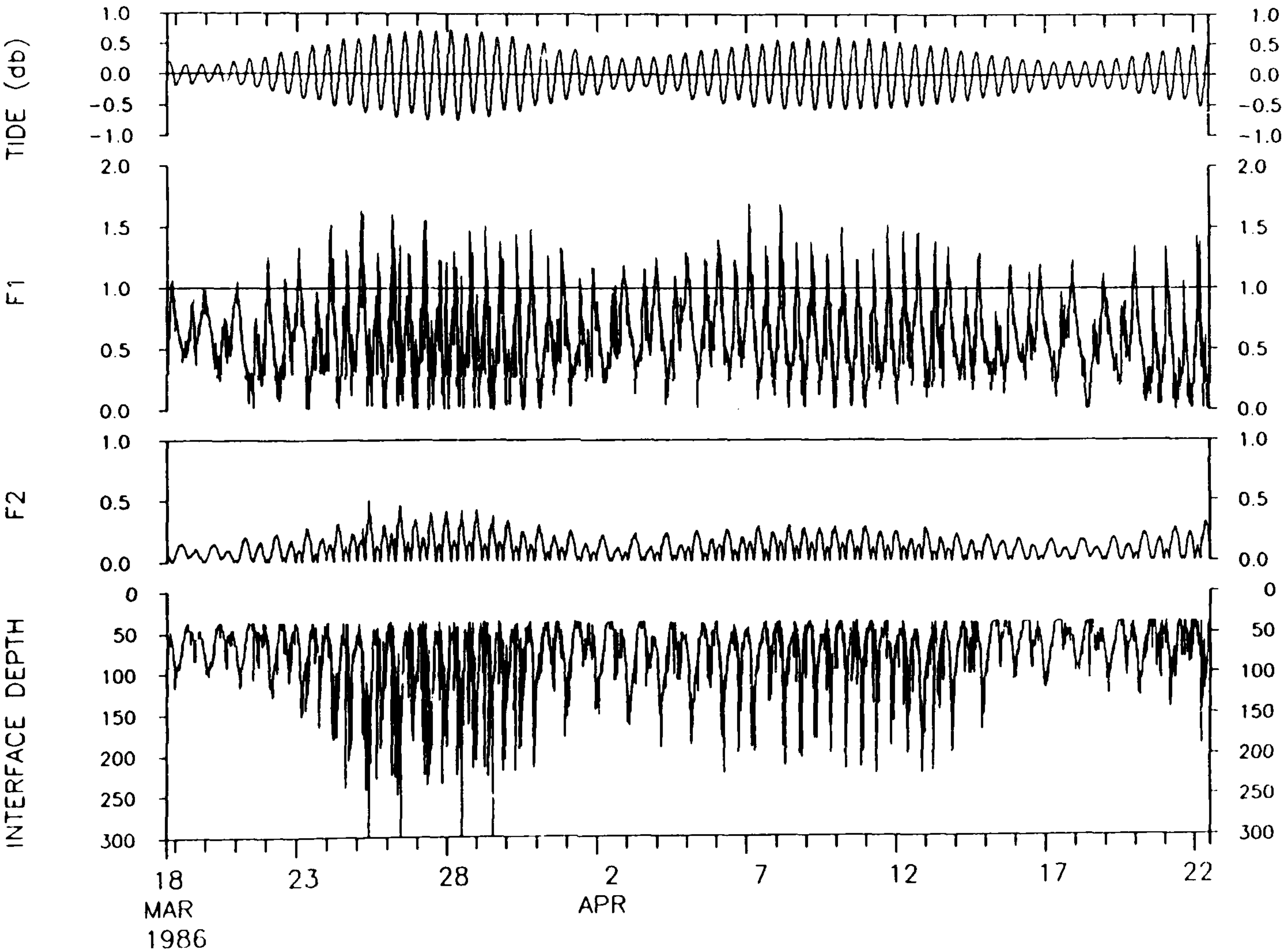

Figure 3. Time series plots of the upper layer internal Froude number (F1), the lower layer internal Froude number (F2), and the depth of the interface. The spring-neap tidal cycle is shown for reference.

AIRBORNE SAR EXPERIMENT IN THE STRAIT OF GIBRALTAR
22 - 24 June 1986

C. Richez

The specific objective of this experiment was to study the periodic generation of internal waves at the sill of the Strait and their propagation along the Strait during two successive semi-diurnal tidal cycles.

For this study we used an Airborne X-band Synthetic Aperture Radar VARAN-S belonging to the French Space Agency (Centre National d'Etudes Spatiales - CNES), on board a B-17 airplane belonging to the National Geographical Institute (I.G.N. = Institut Geographique National). The interest in using an airborne SAR was to be able to follow during two complete semi-diurnal tidal cycles the space and time evolution of the studied process. Though the tidal cycle is essentially semi-diurnal in the Strait of Gibraltar, we also wanted to evaluate the effect of the diurnal component of the tide in repeating our survey at 24 hour intervals.

This objective has not been totally reached since available flying time had to be reduced from 24 to 16 hours for cost limitations, and after that the first trial could not be done in April 1986 due to a radar failure.

The experiment was then postponed to late June 1986, during spring tides. Two overflights were conducted: the first one on June 22, 1986, from 8h 09 UT to 18h 28 UT, that is from about HW - 5h 40 to HW + 4h 30, based upon the predicted high water (HW) in Tarifa at 13h 52 UT (C = 92). The second one was on June 24, 1986, from 3h 13 UT to 9h 25 UT, that is from about HW to HW + 6, based upon the predicted HW in Tarifa at 3h 12 (C = 90). The aircraft was based at Malaga airport, and the hours indicated above are those of the beginning and the end of the survey over the Strait of Gibraltar.

The altitude of the plane was about 3000 meters. The swath of the radar is about 10 km, and the Strait, in its narrowest part, is about 20 km wide. The radar was sampling on the right of the airplane axis and we decided to work on two axes, AB and CD (Fig. 1):

Axis AB was flown from east to west, with the radar looking northwards, and CD was flown from west to east, the radar looking southwards. So there was a small overlapping between the two axes. Twenty axes were sampled during the first flight.

For the second flight, we shortened the axis, and sampled closer to the coasts. We realised 18 axes during 6 hours.

Digitized data covering 45,000 km^2 are now being processed. Images of 10 km x 10 km scenes will be produced with a resolution equal to 9 meters. Quick looks show preliminary interesting information about the studied processes. A detailed report has been sent to the Gibraltar Experiment participants.

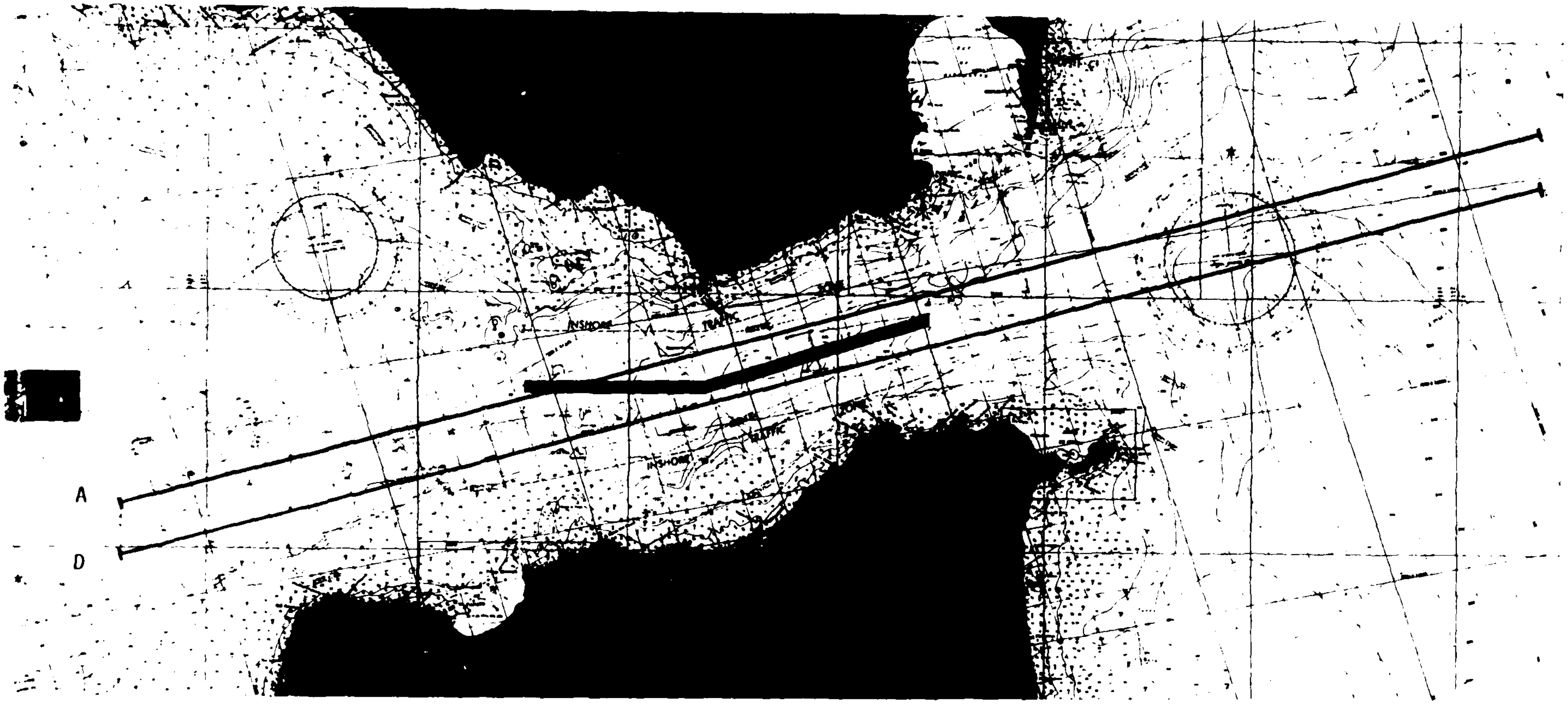

Figure: 1 PATTERN FOR 1ST FLIGHT JUNE 22, 1986

from HW−5.40 to HW+4.45 HW at Tarifa: 13h52 (UT), (C=92)

20 Axis of ca.115 Km each

OBSERVATIONS OF WATER MASSES IN THE STRAIT OF GIBRALTAR

A. Ruiz, P. Villanueva and F. Morales

Summary

From 35 CTD stations obtained in the Strait of Gibraltar during October 1986, the different water masses are separated according to their salinity, potential temperature and potential density characteristics. It is clear that the surface Atlantic inflow into the Mediterranean enters on the south side of the Strait while the Mediterranean outflow has a tendency to exit deeper on the northern side. This is evident principally at the sill.

Introduction

To understand the dynamics of flow through the Strait, a scientific project named "Gibraltar Experiment" (Bryden and Kinder, 1986) has been created which included an oceanographic cruise on board B.H. TOFINO to make CTD measurements (Ruiz et al., 1986). The CTD data in the Strait has been analyzed and the results are presented here.

Methods

During 18 to 22 October 1986, 35 CTD stations were made from the B.H. TOFINO with a new Neil Brown Smart CTD (conductivity-temperature-depth) in the area shown in Figure 1. The navigation system was radar, the maximum depth of the casts was 600 meters. If the water depth was shallower than 600 m, the CTD was brought to a depth 30 m above bottom.

These stations were subdivided into four sections; the first is at the Sill, stations 15 to 22, made in the time between four hours after High Water until four hours before the next High Water; the second section crosses the Strait south of Tarifa, stations 23 to 30, made from two hours before until five hours after High Water; the third is the Cires section, stations 31 to 38, from Low Water until one hour after the next High Water; and the fourth section between Gibraltar and Ceuta, stations 40 to 49, made from four hours after a High Water until two hours after the next High Water.

These stations were processed at the Woods Hole Oceanographic Institution with procedures described by Fofonoff, Hayes and Millard (1974). There were no water samples for the calibrations, so two different methods of calibration were investigated. The first used a comparison of salinity values at $\theta = 12.87$ (Bryden et al., 1978) and the other used an analysis of the distribution of the θ values versus salinities $37.8°/_{oo}$ and $38.0°/_{oo}$. No distinguishable trend in the CTD data and no substantial differences from historical data were found, so no changes were made to the original data. For the geostrophic velocity calculations (Table I) we chose the reference level to be the mean depth of the $37.5°/_{oo}$ isohaline.

Discussion

For the determination of different water masses and the interface between Atlantic and Mediterranean Waters we made profiles of salinity, S, potential temperature, θ, and potential density, σ_θ, for each section.

In agreement with various authors (Boyce, 1975; Lanoix, 1974; Lacombe and Richez, 1982) we took the values of σ_θ = 27.0, 28.0 and 29.0 for separation of four water mass groups; for σ_θ less than 27.0, the water is undiluted North Atlantic Central Water (NACW). From 27.0 to 29.0 there is a mixture of Atlantic and Mediterranean waters with the σ_θ = 28.0 isopycnal marking 50 percent of each water mass and with proportionally increasing NACW percentage for lower σ_θ. Values greater than 29.0 indicated Mediterranean Water, either Levantine Intermediate (LIW) (maximum salinity and potential temperature) or Deep Water (DW), ($\sigma_\theta \geq 29.10$, $\theta \leq 12.9$) (Bryden and Stommel, 1982).

Section IV (Figure 2) occupies the eastern entrance of the Strait, between Gibraltar and Ceuta, exhibiting a maximum bottom depth of 900 m but with data only in the upper 500 m. A thin NACW layer slightly thicker to the south was observed at the surface, with its depth increasing markedly in mid-Strait between stations 45 and 44. In the layer of mixed waters the predominant water is Mediterranean (Figure 2). Below a mean depth of 250 m the water is completely Mediterranean Water. There are many salinity and temperature inversions; most of all for $\theta < 13$ and $S > 38.43$. The interface between Atlantic and Mediterranean Water (σ_θ = 28.0, Boyce, 1975) changes from 60 m in the North (station 48) to 170 m in the South (station 41) with a 0.3° mean slope.

Section III, the Cires section across the narrowest part of the Strait (Figure 3), has much less area than section IV although its maximum depth of 900 m equals that of the Gibraltar-Ceuta section. To maintain the flow in and out of the Strait requires an increase in the geostrophic velocity (Table I) and hence in the slope of the density surfaces. On this section, the depth of the NACW layer increases to the south, decreasing the area of mixed water. The sharp increase in depth again occurs in mid-Strait at station 38 and then increases more slowly to the south. Below 250 m mean depth, the water is completely of Mediterranean type. The mean transversal slope is 0.5° and the interface depth (σ_θ = 28.0) varies from 70 m (station 35) in the north to 190 m (station 31) in the south.

Section II (Figure 4) crosses the Strait south of Tarifa. In relation to the previous sections, the maximum depth has decreased by 30 percent to 640 m and so the Mediterranean Water area has decreased significantly. There is a large increase in the geostrophic velocity (Table I) indicating stronger slope of the interface across the Strait. The NACW layer is substantial on the south side of Section II. Station 27 in mid-Strait marks a sharp change in the pycnocline such that the undiluted Mediterranean Water is drastically diminished on the south side of the section. On the north side of this section, the layer of NACW is much thinner than in the previous section, but the mixed and undiluted regions of Mediterranean Water are similar to the previous section. The mean transversal slope along the section is 1.2°. Also interesting is the slope between stations 27 and 28 where the isotherms and isohalines exhibit a large change in slope to 8.2°.

Section I (Figure 5) corresponds to the Sill of the Strait of Gibraltar where theoretical hydraulic control models for the Strait assume the flow becomes critical (Bryden and Stommel, 1984). South of station 19, the NACW layer occupies more than 70 percent of the area. Continuing in depth, layers of Atlantic diluted water and Mediterranean diluted water cover the undiluted Mediterranean Water which is very thick on the north side and totally absent on the south side of the Strait. In station 17, there is a large inversion in salinity and temperature (Figure 6a and b) about 40 m above bottom with $S = 36.85°/_{oo}$ and $\theta = 14.08$ corresponding to diluted NACW flowing at high velocity into the Mediterranean Sea. North of the Sill (which is at station 19) the water in the lowest 40 m is Levantine Intermediate Water. We have not detected undiluted Deep Water flow on the Sill section.

The calculation of mean transversal slope for the interface ($\sigma_\theta = 28.0$) across the Sill section (I) from 20 m at station 17 in the north to 260 m at station 27 in the south yields a value of 1.4°, representing the largest value of all sections.

Conclusion

From the data, taken over five days, there is clear evidence of the Coriolis effect in the Strait of Gibraltar. In the southern half, it is characteristic to observe principally Atlantic inflow water. On each section in mid-Strait, there is a marked change in depth of the Atlantic layer at stations 45-44, 38-32, 27-28, 19-18 (Figure 1). South of a hypothetical line joining these stations, Atlantic water dominates the water column. Also the Coriolis effect forces the outflowing Mediterranean Water to be north of this hypothetical line. The Mediterranean Water banks from mid-section up onto the Spanish continental slope.

The Deep Water signal decreases from the Gibraltar Section to the west and is not detected at the Sill. In the same way, the interface between Atlantic and Mediterranean Waters slopes in a cross-strait direction with a slope that is four times greater at the Sill than at the Gibraltar section.

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TABLE I: Geostrophic Velocity in the Strait Section (cm/sec)

Sections	I	II	III	IV
Stations	21-17	25-28	36-32	48-41
Depth				
0	399	528	140	60
50	335	409	153	65
100	131	161	100	24
130	0	0	22	0
140	-44	-50	0	-7
150	-88	-94	-20	-15
200	-301	-247	-100	-46
300	-	-363	-130	-57
400	-	-381	-133	-62
500	-	-	-136	-

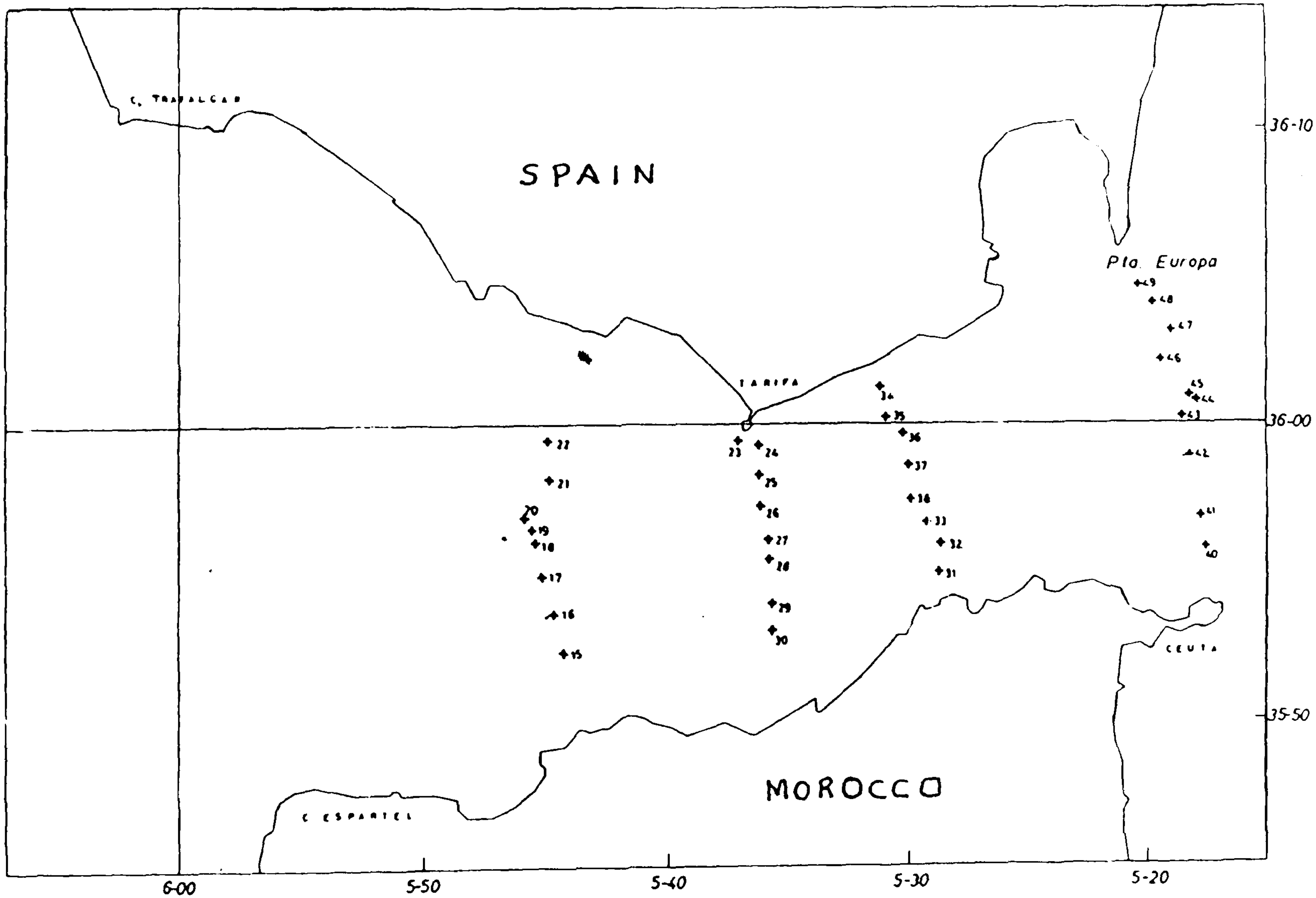


Figure 1. Locations of the CTD stations.

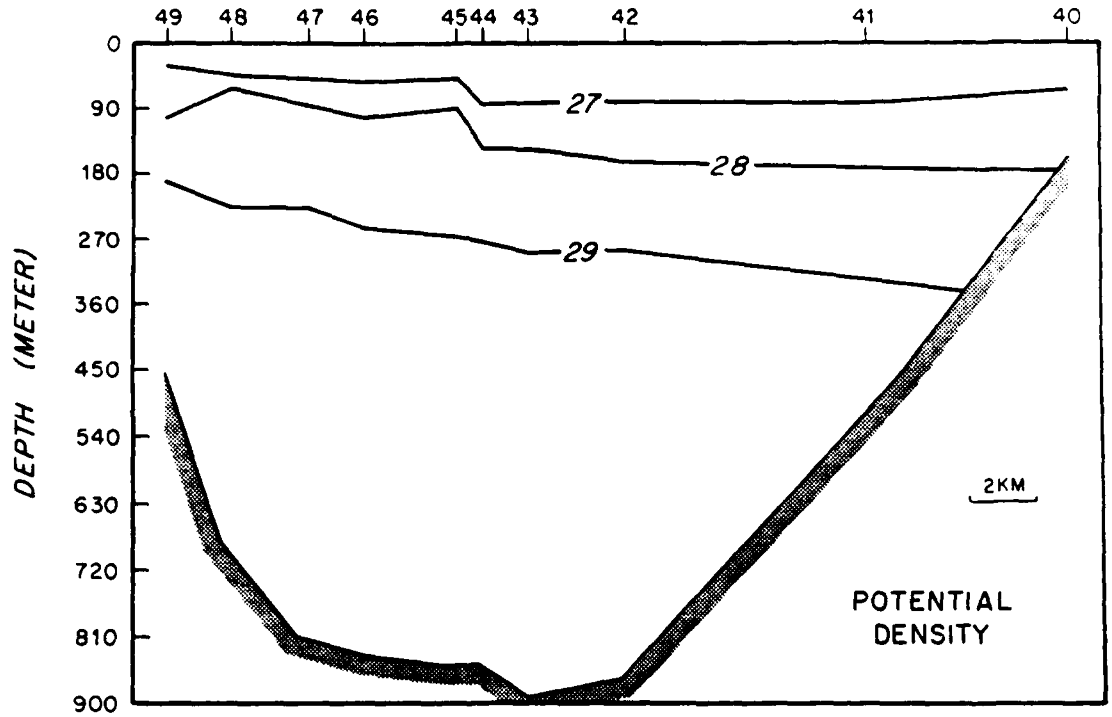


Figure 2. Potential density along section IV, stations 40-49, eastern entrance of the Strait.

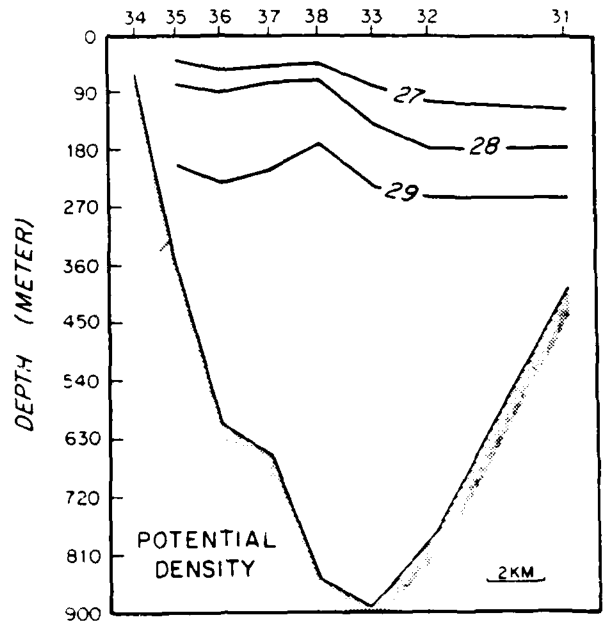


Figure 3. Section III, stations 31-38.

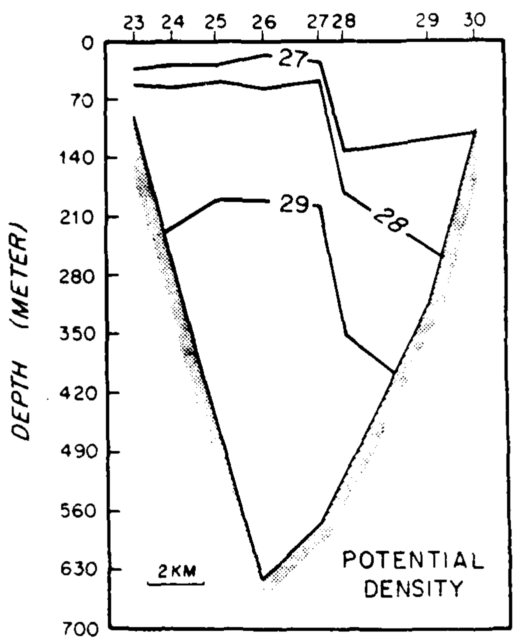


Figure 4. Section II, stations 23-30.

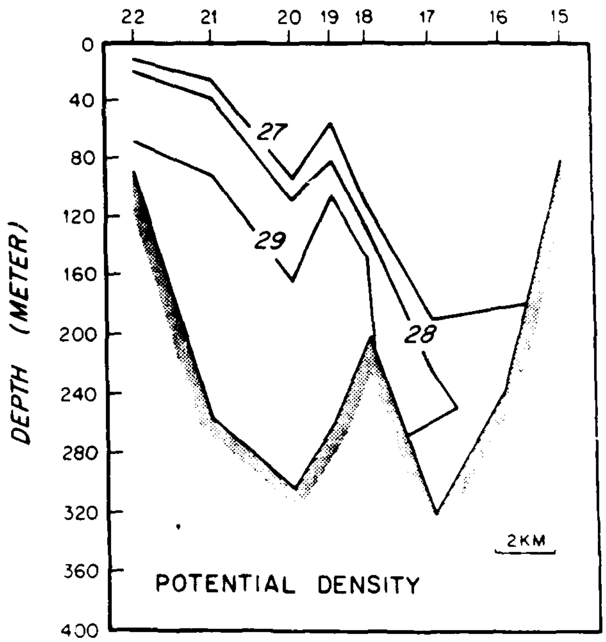
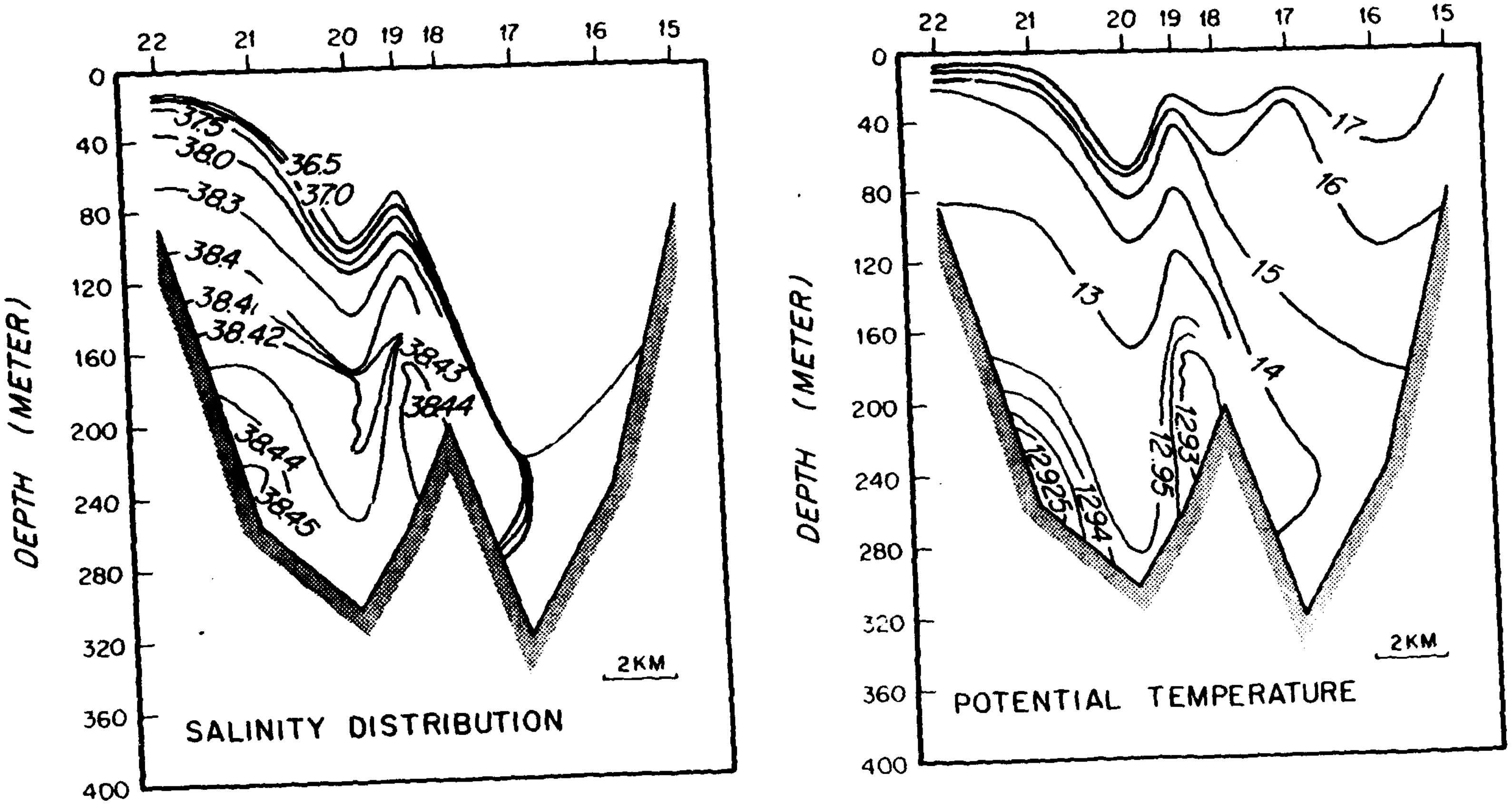


Figure 5. Section I, stations 15-22.



(a)

(b)

Figure 6. Section I, stations 15-22.

RADAR MONITORING OF INTERNAL WAVE SURFACE FEATURES FROM GIBRALTAR

G. Watson

From March 26 to April 29, 1986, a shore-based marine radar at Gibraltar was used to image the surface features of internal waves propagating eastward out of the Strait. The image was recorded at intervals of 3 to 15 minutes.

Sea return was obtained from distances of up to 15 km, within which large features were often clearly seen. During most tidal cycles, a packet of eastward-travelling waves arrived some time between HW+3h30 and HW+8, followed by a packet of northward-travelling 'oblique waves', a few hours later (arriving between HW+7 and HW+9). Some other wavelike features were also occasionally seen. The timings of these waves varied systematically throughout the spring-neap cycle (Fig. 2), although in slightly different ways during the two cycles observed. During neaps, wave packets were seen only on alternate cycles. Wavelengths, periods and speeds of the main packets were similar to previous measurements. These have only been measured for a limited number of packets so far.

A further deployment was made during June 21-24, to coincide with the rescheduled airborne SAR overflights of C. Richez. Preliminary comparison of the two data sets has revealed two wave packets imaged by both radars, and one (unexpectedly off Gibraltar at HW) imaged only by the SAR.

Experimental Details

Radar: X-band (3.2 cm), 25 kW peak power.
Resolution 100 m x 1 deg.
Mounted in vehicle at 100 m elevation (Windmill Hill, Gibraltar).
Used on 22 km range, but return out to about 15 km.
Down time 27h (3%).

Images on 35 mm B&W film - 800 frame sequences. Some slightly spoiled in processing, but most features still visible.

Other data available:
Hourly wind at Gibraltar Airport
Meteorological observations from Europa lighthouse
Photographs of sea surface, taken from site.

Figure 1 shows some typical images observed.

Figure 2 illustrates the way in which the arrival times of the main packets varied throughout the experiment. Odd and even cycle numbers are differentiated in order to emphasize the strong diurnal variation.

Table 1 summarises the period covered by each sequence of images, and indicates major losses of data.

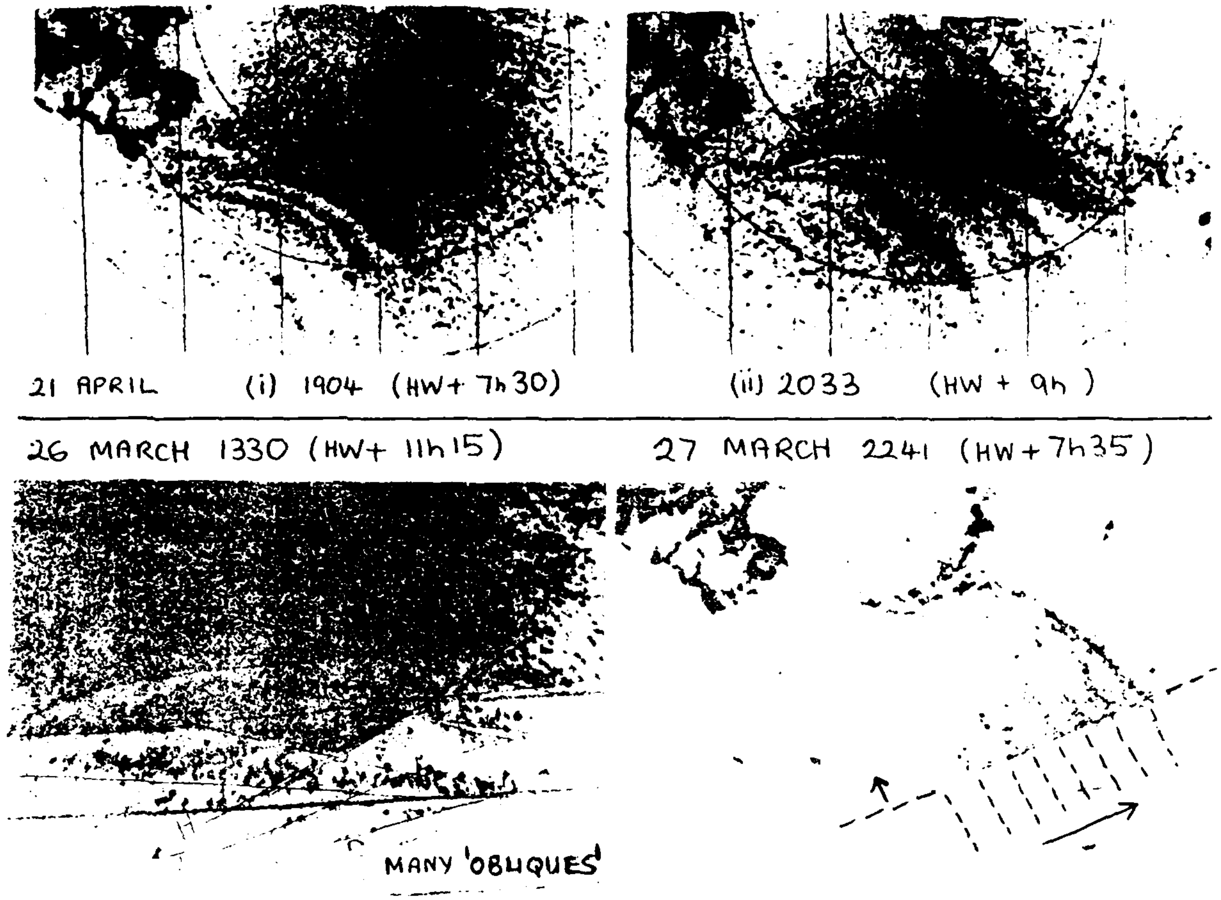


FIG 1 – SAMPLE IMAGES (NEGATIVES)

FIG 2 – ARRIVAL TIMES AFTER HIGH WATER AT 5°19' W, 36° 01' N. | o Even Cycles + Odd Cycles | Cycle 0 : 26 MAR 86 from 1427

More details are available in a report in preparation for the Admiralty Research Establishment, Portland, Dorset, who funded this work.

Table 1: Summary of Radar Coverage

Sequence	Start (GMT)	End	Timestep (mins)	Packets	Obliques	Comments
March 1986						
3	25.1733	25.1735	-			
4	26.1044	26.1523	10	1	1	
5	26.1657	28.1018	15	1	3	
6	28.0946	30.1835	15	5	5	
7	30.1940	02.0800	14	4	3	
April 1986						
8	02.0810	02.1618	14	1		
	02.1618	02.1845	4			
	02.1845	02.2230	14			
	02.2230	03.0840	14	***	***	No image
	03.0840	04.0908	14	1		
9	04.0938	04.1810	14	1		
	04.1810	04.2055	5			
	04.2055	05.0840	14			
10	05.0947	07.0640	15	4	4	
	07.0640	07.1200	5		1	
11	07.1227	08.0640	15	2	1	
	08.0640	08.1704	10		1	
13	08.1754	09.0502	3	1		Unclear
14	09.0533	10.1718	3	3		
15	10.1802	11.0714	3	1	1	
	11.0721	11.1135	3	***	***	No image
	11.1141	11.1439	3		1	
	11.1442	11.1646	3	***	***	No image
	11.1702	11.0802	15	1	1	
	12.0816	12.1904	3	1	1	
16	12.1934	12.2020	3	1		
	12.2020	14.0755	6		2	
17	14.0815	14.1349	3	1		
	14.1356	17.0845	10	3	1	
18	17.0855	19.1412	10	1		
	19.1414	19.1803	3	1	2	
	19.1806	19.1928	3	***	***	No image
	19.1934	20.1050	3			
19	19.1059	20.1120	3			
	20.1123	20.2015	3	***	***	No image
	20.1900	21.0320	3	2		
20	21.1651	29.1451	15	10	10	
June 1986						
21	21.1555	22.0700	15	2	1	
22	22.0730	23.0730	5	3	3	Some gaps
23	23.0740	24.0820	5	2	1	Some gaps

PRESSURE MEASUREMENTS

C. Winant, A. Ruiz and J. Candela

There were three main objectives that motivated the pressure measurements during the year-long Gibraltar Experiment; they were:

- Relate pressure differences across and along the Strait at different depths with the flows in the deep and shallow layers, at subinertial and tidal frequencies.

- Investigate the effects of temperature, salinity and density fluctuations on the pressure field.

- Describe and understand the behavior of the tidal wave and its relation to the subinertial flows.

To accomplish these objectives 6 bottom pressure recorders (BPR) were installed at the places shown on the instrument location chart. Two were positioned along the axis of the Strait at either side of the Camarinal Sill: Deep West (DW at 210 m depth) and Deep East (DE at 450 m depth). Four were positioned across the Strait along the Camarinal Sill: Shallow North (SN at 10 m depth), Deep North (DN at 210 m depth), Deep South (DS at 210 m depth) and Shallow South (SS at 10 m depth). These instruments were constructed at SIO and recorded pressure, temperature and conductivity at one minute intervals. In addition the Spanish Navy Hydrographic Institute (IHM) installed three shallow Aanderaa pressure sensors in the ports of Tarifa, Algeciras and Ceuta. These instruments recorded pressure and temperature at 10 minute intervals.

All instruments were serviced at least once during the one-year experiment, and the data return from each instrument is illustrated in the time chart.

During the recovery and redeployment of the BPRs in spring of 1986, two thermistor chains were installed at a northern (TCN) and southern (TCS) location on the Camarinal Sill in 200 m of water (near the BPRs DN and DS, respectively). These chains recorded temperature at 14 depths (30, 40, 50, 60, 70, 80, 90, 105, 120, 135, 150, 165, 170, and 195 m) every 4 minutes. The data return from these instruments is also shown in the time chart.

Notes on the Performance of the Instruments

The Aanderaa pressure sensors from the IHM had an overall excellent performance except the instrument at Tarifa that had battery problems which resulted in two data gaps during the first six months of deployment.

The BPRs had some problems, but considering that these instruments are still in the development stage, their performance was remarkable. The instrument at DE station was not recovered due to a malfunction of the acoustic release. Since this was the only instrument equipped with a pressure sensor (0-900 psi) capable of measuring at those depths (450 m), the station was not re-occupied during the spring of 1986. The instrument located in the shallow Moroccan coast (SS) was moved from its initial deployment position by (our guess) winter swell from the North Atlantic, and, even though we were able to find pieces of the anchor, the instrument itself was not recovered. We had a second instrument deployed at this station during the spring of 1986. This second deployment resulted in good pressure observations, but no temperature; something similar happened to the instrument at DN during its second deployment.* The tape drive of the instrument at the DW station malfunctioned during the spring 1986 deployment and no data was recorded. Also during this second deployment phase the instrument at the DS station broke off from the anchor assembly and was not recovered.

The thermistor chain located at the northern end of the Camarinal Sill (TCN) had electronic problems in the recording circuit and only recorded for two months instead of the five it was supposed to have sampled. The thermistor chain to the south (TCS) performed as expected. The data from these two thermistor chains is of reasonable quality.

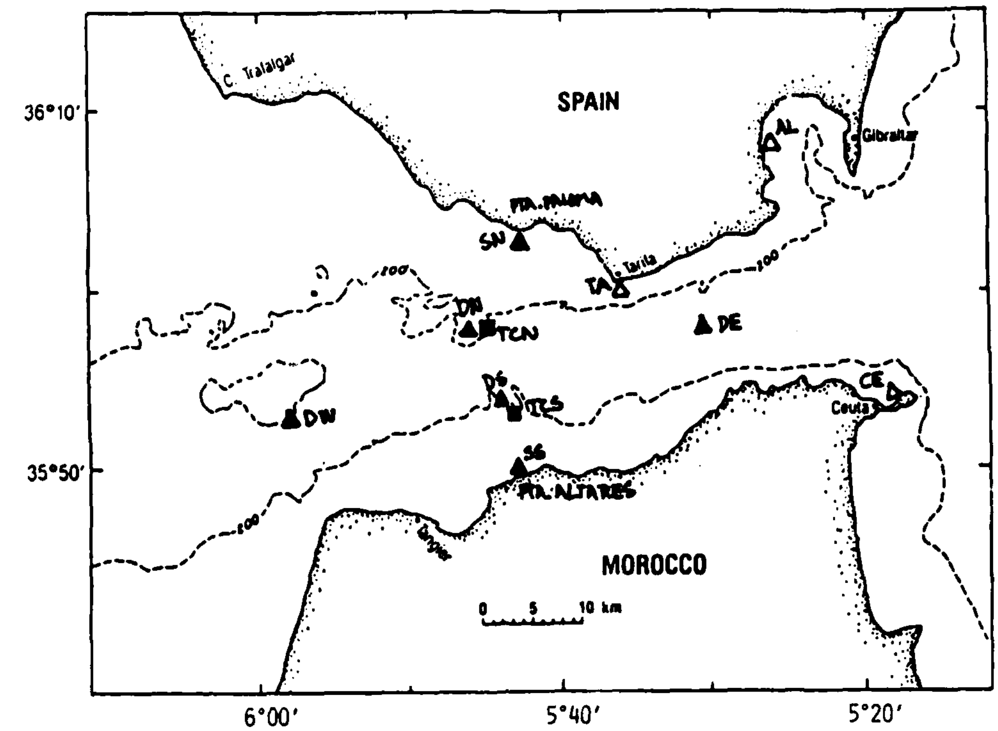
Comments on Preliminary Results

Up to now the preliminary results are very encouraging and the pressure, temperature and salinity data obtained from the instruments seems to be of excellent quality. A comparison of the pressure differences across the Strait with the current meter data obtained by Bryden, Milleiro and Pillsbury confirms that to first order the flows along the Strait are in geostrophic balance both at subinertial and tidal frequencies. A good preliminary description of the principal tidal constituents has been accomplished and a refinement should be possible as more data becomes available.

Locations of Instruments

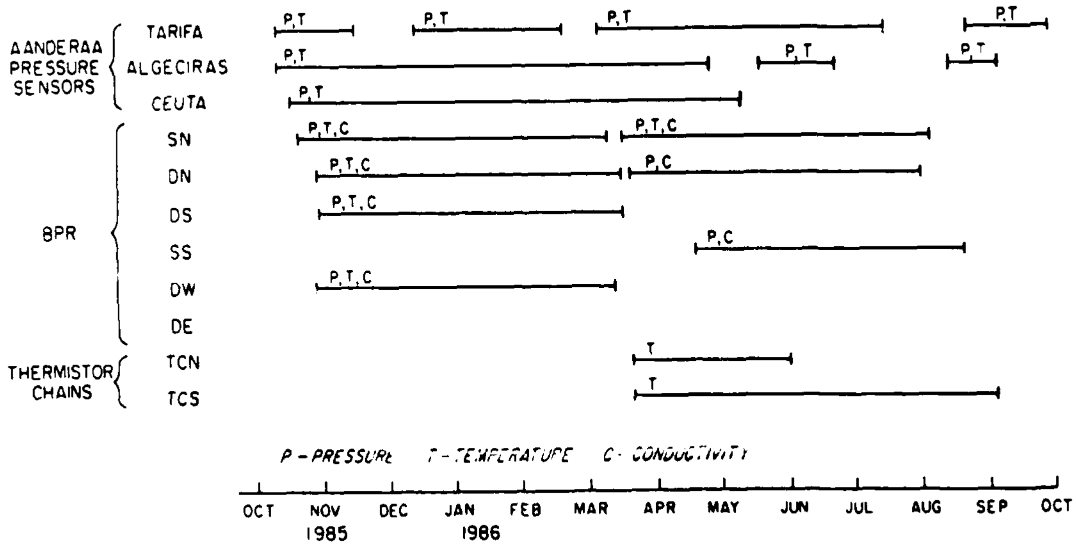
1)	Tarifa (TA)	36°01'N	5°36'W
2)	Algeciras (AL)	36°08'N	5°26'W
3)	Ceuta (CE)	35°53'N	5°18'W
4)	Shallow North (SN)	36°03'N	5°43'W
5)	Deep North (DN)	35°58'N	5°46'W
6)	Deep South (DS)	35°54'W	5°44'W
7)	Shallow South (SS)	35°50'N	5°43'W
8)	Deep West (DW)	35°53'N	5°58'W
9)	Deep East (DE)	35°58'N	5°31'W
10)	Thermistor Chain North (TCN)	35°57'N	5°46'W
11)	Thermistor Chain South (TCS)	35°54'N	5°43'W

* Since conductivity is a strong function of temperature, we hope to recover the temperature signal from the conductivity, but we are not going to be able to compute salinity for these instruments.



▲ Bottom pressure sensor (SIO) [P(t), T(t), S(t)]
△ Aanderaa pressure sensor (IHM) [P(t), T(t)]
■ Thermistor chain [T(t,z)]

TIME CHART



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16. Abstract (Limit: 200 words)

During the period October 1985 to October 1986 a large group of oceanographers collaborated in an intensive field effort called the Gibraltar Experiment. Scientists from Morocco, Spain, France, the United Kingdom, Canada and the United States joined together to obtain an extensive suite of measurements which greatly enlarged the oceanographic data base for the Strait of Gibraltar. Primary experiment goals included obtaining one realization of the annual flow cycle, understanding the dynamical balances of the strait flow, developing strategies for long-term monitoring of the Strait, and increasing knowledge of strait effects on the adjacent ocean. Preliminary results show progress toward each of these four goals.

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